METAL TRANSFER IN THE WEAR PROCESS: INFLUENCE OF PARAMETERS

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Department of Naval Architecture and
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Chairman, Departmental Committee
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Submitted to the Department of Naval Architecture and Marine Engineering on 20 May 1957 in partial fulfillment of the requirements for the degrees of Master of Science in Naval Architecture and Marine Engineering and Naval Engineer.

ABSTRACT

In order to provide further information about the basic process involved in the wear of metals, experiments have been made with radioactive and inactive mild steel pins rubbing against a hardened steel ring.

Using radioactivity methods, transfer of metal between the rubbing surfaces was determined concurrently with measurements of the total wear.

In experiments at various loads and speeds, the relationships between the rates of transfer and wear were studied. The results indicate that the wear process consisted of three stages as pointed out by Kerridge: transfer of metal, oxidation of the transferred layer, and the subsequent removal of the oxide to form a loose wear product.

Two distinct rates of wear were found, which coincide with two distinct regimes of metal transfer. The transition in wear rates and transfer rates was found to occur at the same number of revolutions, independent of speed, for tests at the same load.

The product of load times number of revolutions to transition in wear was found to be approximately constant over a wide range in loads and speeds for both these experiments and those of Kerridge.

The proposed mechanism for the initial wear phase is metal transfer alone. The increase in wear rate in the equilibrium phase is suggested to be caused by the heat insulating properties of the oxide.

Thesis Supervisor: Brandon G. Rightmire
Title: Associate Professor of Mechanical Engineering

Cambridge, Massachusetts
May 20, 1957

Professor Leicester F. Hamilton
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge 39, Massachusetts

Dear Professor Hamilton:

In accordance with the requirements for the degrees of Master of Science in Naval Architecture and Marine Engineering and Naval Engineer, we herewith submit a thesis entitled, "Metal Transfer in the Wear Process: Influence of Parameters."

Respectfully,

ACKNOWLEDGEMENT

The authors wish to express their gratitude to Professor Brandon G. Rightmire, thesis supervisor, for his continued interest and encouragement; his aid during the course of this work was deemed incalculable.

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I. INTRODUCTION

The mechanism of wear between solid surfaces is a complex process, influenced by so many variables that caution must be exercised in interpreting the most carefully controlled laboratory experiment. Often even the slightest change in the operating conditions may change the entire nature of the wear process.

Both metal transfer and wear produce serious effects on moving parts. The relationship between metal transfer and wear is a basic step which must be understood if wear is to be predicted.

Among the several recognized types of wear (Burwell), the most fundamental type is residual wear, that type of wear which takes place whenever two solid surfaces, lubricated or not, are in rubbing contact. It remains when all other types of wear are eliminated.

Attempts have been made to develop a theoretical basis to explain the wear process. It is a generally accepted fact that the formation and rupture of the welded junctions is an important factor in the wear of metals (Bowden and Tabor, 1950). Generally speaking, appreciable friction and metal transfer will take place only when continuous metallic junctions are established between two contacting surfaces.

To those who have suggested that metallic adhesion is the reason for the formation of continuous metallic junctions, I-Ming Feng (1952) pointed out that the adhesion of perfectly clean metallic surfaces could not be of primary importance

in friction and metal transfer, because friction does exist and metal transfer does take place in the absence of adhesion.

In his theory he suggests that metal transfer and wear take place at the plastically deformed high spots of actual contact. The interface of a pair of plastically deformed high spots is roughened as the result of the plastic deformation. The roughened interface of the contacting high spots gives a strong mechanical interlocking effect which is the primary cause of metal transfer and friction when the tangential force causes shearing in the softer metal around the interface. The heat liberated in shearing is conducted through the interface as a temperature flash, causing welding.

Largely from empirical data, other workers have attempted to formulate theories to explain the simplified wear conditions used. Some of these theories involve: the number and nature of the local encounters between two atoms, one of these on each of the opposing surfaces (Holm, 1946, Burwell and Strang, 1952); the same approach to the encounter between two surface asperities (Archard, 1952, 1953); an analysis of the number and size of the wear particles produced, embodying a constant "wear coefficient."

In all these works, the primary concern has been to explain the mechanism of the wear process to pave the way for a rational approach to the practical problem of wear prediction.

If there be such a simplification, two "rules" of wear seem to be that the wear rate is independent of the apparent

area of contact and that the wear rate is proportional to the applied load for unchanged surface conditions.

Recent investigations to find out to what extent these rules of wear apply to all materials are noteworthy (Archard and Hirst, 1956). Using a wide range of materials chosen at random, they found that an equilibrium condition must be attained for such rules to apply.

By equilibrium they meant that in the initial rubbing of the new surfaces, changes occurred in the condition and structure of the surface layers, which tended to stabilize after a time. During this initial period they found that the wear rate often changes with time, but became constant with equilibrium of the surface. Similar conclusions were reached by Hirst and Lancaster, 1953.

Several attempts have been made to establish the mechanisms by which wear particles are produced, through study of the metal transfer from one rubbing surface to the other (Rabinowicz and Tabor, 1951; Rabinowicz, 1953). The main difficulty in this approach is that metal transfer is generally agreed to be caused by intermetallic welding, and welding does not in any obvious way lead to the production of loose wear particles. Apparently the relationship between metal transfer and wear particle production is not a direct relationship.

Kerridge (1955) made a study of wear using a radioactive tracer technique and proposed the theory that the wear process for steel on steel was a four-step operation rather than the one-step process other workers had considered.

He collected wear and metal transfer data which indicated that the wear process consisted of the following steps: (i) removal of material from one test piece by welding transfer to the other, (ii) the building up of a layer of this material, (iii) the oxidation of this layer, and (iv) the removal of the oxide to form wear debris.

Thus, when the test pieces first begin to rub together, localized welding takes place, and material is transferred from the soft pin to the much harder ring. He found that at this stage the wear rate was greater than the wear rate under steady conditions of surface layer. The welding can of course take place only at the actual regions of contact, and, since these are continuously changing, a layer of transferred metal gradually forms over the whole of the wear track on the ring.

He believes that the high temperature developed at the actual contact regions causes the transferred material eventually to oxidize, and the oxide, not being strongly adherent, is subsequently rubbed off. At equilibrium the transferred layer is being removed in this way at a steady rate, and the wear of the pin consists of welding and transfer to the regions of the original ring surface that become exposed. A balance then exists between the wear of the pin and the rate at which loose wear products are formed.

By using a combination of radioactive and inactive test pins the rate of transfer to the ring in the equilibrium condition was estimated and found to be the same as the wear rate of the pin.

The combination of radioactive tracer methods with the more usual type of wear measurement permits a study of the relationship between wear and metal transfer. It is the purpose of this paper to check Kerridge's theory on the stages of the wear process between unlubricated steel surfaces by an independent investigation. The extension of this work of his to other parameters is believed to be necessary for a more thorough understanding of the wear process.

II. PROCEDURE

The machine used for the test is shown in Figure 23. It is basically a simple pin and ring apparatus. In this equipment a flat-ended pin is loaded against the cylindrical surface of a rotating ring and the wear of the pin is determined from the dimensions of the wear scar produced on it. Appendix A is an example of the calculations used in determining this wear. The lathe was driven by a variable speed Graham Drive. The lathe faceplate assembly was machined in place with a tapered collar to position accurately and rotate the hardened steel bearing cups used as our cylindrical surface. The pin holder and pins had scribed marks which enabled us to replace the pin after each scar measurement so as to have the same surface alignment between the rubbing surfaces. There was an atmospheric shield which surrounded the cylinder during the experiment and to which was connected a dry compressed air supply. This supply is shown in Figure 25. Air from a tank of dry compressed air was led successively through a sodium hydroxide dehumidifier and a copper coil immersed in liquid nitrogen to ensure that no moisture remained in the atmosphere around the cylinder. The speed was carefully checked with a tachometer during the runs to ensure that it remained constant. The cylindrical surfaces were scrubbed in two successive baths of benzene to remove any oil and then were given a final surface finish with 4/0 abrasive to remove the benzene film coat. This preparation of the cylinder

was done immediately before starting a run to reduce the possibility of the surface becoming contaminated.

The pins were lapped to a true plane surface which was checked by an optical flat and by a Measuring Comparator (64X). They were then given the same benzene and final abrasive treatment described above. The alignment between the pin and the cylindrical surface was carefully checked before each run.

After the desired length of run, the pin was removed from its arm and the scar was measured by optical microscope at a magnification of 50X.

In determining the amount of metal transferred to the ring, radioactive pins of the same material were used. These pins were made radioactive by pile irradiation at the Brookhaven National Laboratory. The measurement of the amount of activity transferred was made by removing the entire face plate assembly from the lathe in use and mounting it in a similar lathe which had been converted into a lead castle. This is shown in Figure 26. Measurements were made by a Geiger-Muller tube and calibrated scaler. The tube was placed at a millimeter's distance from the wear trace, and the trace was rotated by the lathe.

These measurements of activity were compared to standards of known concentrations of the radioactive pin. We prepared these standards by dissolving a known amount of radioactive pin in nitric acid and diluting this solution to our estimated strength of trace to be measured. This solution was then deposited by micrometer pipette on a

slowly moving mild steel plate and evaporated. We were thus able to prepare standards with known amounts of radioactive iron per cm length.

The pins were mild steel pins, carbon .21%, manganese .95%, silicon .08%, hardness 91 Rockwell B (Brinell Hardness 190). The face dimensions were 6.36 mm square.

The rings were Timken Bearing Cups #6220, O.D. 12.7 cm., width 3.81 cm. Their hardness was 61 Rockwell C (Brinell Hardness 614).

III. RESULTS AND DISCUSSION

Wear

The wear curves as a function of load are shown on Figures 1-3, and are combined in Figure 4. It was observed that three distinct regimes of wear were characteristic at all loads. These we label as initial, transition and final wear.

On starting the run we found an essentially constant wear rate, the surface of the cylinder showing a patchy grey track. As the run progressed, this track became nearly uniform to the eye, and at some point in time the surface of the track began to appear reddish. At this point we found that our initial wear rate began to increase, and after a short transition period our track had become rusty red, and the wear rate once more became constant at a higher rate of wear.

The effect of load on the wear process seems to be two-fold. First, an increase in load causes an increase in wear rate for both the initial and the final wear rates. This variation is shown on Figure 5. This effect of load has been found by many workers, and is considered one of the "rules" of wear. Secondly, an increase in load causes the transition in wear to occur earlier. This suggests that an energy state of the wear surface plays an important part in the wear process.

It is also noted that the total wear to the transition point increases with load. This indicates that the energy input is more important to the wear process than is the

amount of material transferred.

In passing, we also noted that the constant wear rates were indicative of the independence of wear of the apparent area of contact. This has been quite thoroughly investigated by others.

Our next move was to investigate the effect of speed, maintaining the load constant at 500 g. Figures 1, 6-8 present the wear data taken for a range of speeds between 380 and 95 RPM (252-65.4 cm/sec.). Wear curves of the same type as before were found. Again we found initial constant wear rates, with a transition occurring on the appearance of red oxide and the wear rate increasing to a constant final rate. The wear tracks duplicated in appearance those made in the investigation of the load parameter. Time or distance is not a useful criterion for comparison of the effect of speed on wear. More useful in such a comparison is the wear as a function of revolutions. These data are shown on Figure 10.

From Figure 10 we noted that the transition in wear occurred at the same number of revolutions. In Figure 12 we have plotted the variation in wear per revolution as a function of time. The initial wear rate reaches a minimum at about 240 RPM (160 cm/sec.). The final wear rates were obtained for only three speeds. At the lowest speed, (Figure 8), we could detect no evidence of transition. However, when compared on Figure 10, it was observed that this run was terminated before reaching the critical number of revolutions. The curve of final wear per revolution also

showed a minimum point.

The important point to be noted from this parameter variation is the fact that transition (and oxidation) occurred at the same number of revolutions for each speed. Since the load was constant, each track can be visualized as having received the same energy input before oxidation commenced. As in our load parameter runs we conclude that the energy state of the track is critical in determining the wear rate.

This conclusion with regard to the energy level of the transferred layer called for some consideration of the factors influencing this energy state. The most obvious factors were the impact intensity and the number of contacts received by a particular spot on the surface to the initiation of transition.

The product of the load and number of revolutions was found to be roughly constant for all our combinations of load and speed. In addition, using the two load experiments presented in Kerridge's paper, this product was found to be in very close agreement with our data.

An interesting aspect of the effect of speed on the wear process is the minimum found in both initial and final wear curves of Figure 12. This suggests that an interplay between time and temperature exists in the following manner:

a) At the lower speeds more time for deformation to occur exists between surface contacts. Hence, perhaps a greater proportion of these contacts results in transfer of metal than is the case at

the intermediate speeds.

b) At the higher speeds, a higher temperature exists which increases the deformation rate between contacts and results in more contacts transferring metal than at the intermediate speeds.

Transfer

Due to a delay in delivery of the counting equipment, the work on metal transfer as a part of the wear process was of necessity done after the basic wear data were collected. Insofar as we could determine, the wear processes were identical in our transfer runs.

The pins were considerably weaker than we desired, and consequently the precision of our measurements suffered. However, certain definite conclusions can be drawn from the transfer curves we found.

In general, the transfer occurred in three distinct phases as proposed by Kerridge: (i) an initial build-up of layer on the cylinder, (ii) a transition phase, and (iii) an equilibrium phase. In the initial phase the wear particles from the pin are welded to the cylinder surface, and this layer builds up. The equilibrium phase is characterized by the loss of previously transferred metal and its replacement in the surface by an equal quantity of newly transferred metal. The transition phase occurs between the initial and the equilibrium phase.

Figures 13 and 14 are the transfer curves for loads of 500 and 1000 gm. Variation of transfer with speed is shown on Figures 13, 16, and 17.

The equilibrium amount of transferred metal on the cylinder could be explained either as direct loss of pin material without entering the transferred layer or as loss of material from the transferred layer and replacement in the layer of an equal quantity of new pin metal. Using Kerridge's technique, we substituted an inactive pin for the active pin after attaining an equilibrium layer of active material.

Had the wear occurred by direct production of debris from the pin, we would have expected to find the amount of active material in the transferred layer essentially constant. In fact, as can be seen on the transfer curves, the amount of active material showed a sharp and continuous decrease. Since there is no evidence that the layer of transferred metal decreased suddenly, the obvious conclusion is that the active material is being replaced in the transferred layer by an equal quantity of inactive material. Thus, at the equilibrium state, the rate of loss of material from the surface has reached the same level as the rate of wear from the pin. Further, debris production in this wear process is an indirect process, one stage of which consists of the entry into the transferred layer.

It is also apparent from the transfer curves that the rate of removal of active material is greater than the build up of active material. This indicates that the wear rate is larger after equilibrium than for the initial stages.

Only two loads were investigated but for the higher load (Figure 15) the transition occurred earlier and at a

somewhat higher total wear.

The effect of speed on transfer was investigated and these data are presented on Figures 13, 16, and 17. The three curves are plotted together on Figure 18. The most notable feature of this figure is that the transition to equilibrium for all three speeds occurs at the same number of revolutions.

The curves in Figure 18 are observed to give a decrease in equilibrium layer thickness (lower total wear) with an increase in speed. Our investigation of wear (Figure 12) indicated that the final wear per revolution increased with an increase in speed over this range. This indicates that the effect of an increase in speed is to give a smaller layer thickness and a higher wear per revolution for the equilibrium state.

Relation between Wear and Transfer

The preceeding discussion has treated the wear data and the transfer data independently. These data have been combined in Figures 19-22.

A very close agreement exists for all but one combination of load and speed between the times of transition for both wear and transfer. This indicates that the initial wear rate is accompanied by the build-up of the transferred layer, and that the final wear rate is characterized by an equilibrium layer of transferred material.

If this is so, the slope of the initial wear curve and the initial portion (build-up) of the transfer curve should be the same. With the exception of Figure 22, this is so.

Further, the slope of the final wear curve should be equal to the slope of the replacement portion (inert pin) of the transfer curve.

The agreement between the initial slopes of the wear and transfer curves leads us to conclude that for these conditions no debris is produced in the initial phase.

From the speed parameter data it is concluded that debris is lost from the transferred layer only when the transferred material has been raised to a critical energy potential. This energy potential for both our experiment and Kerridge's, embracing a wide range of both speed and load and a considerable difference in hardness of pin, can be expressed as a constant value of the product of load and the number of revolutions.

The equilibrium wear/revolution found by us was higher than the initial wear/revolution. Kerridge found no change in wear/revolution. The only known difference in the initial and equilibrium phases was presence of red oxide on the surface. The suggested mechanism of wear in the equilibrium phase is as follows: The oxide spread over the surface acts as a heat insulating medium. In doing so, the heat flow due to friction is restricted to a smaller proportion of the apparent area of contact. The total heat flow remaining constant, the surface temperature between the surface contacts must increase, resulting in more deformation and higher transfer.

Some support for this theory is found in Figure 12. If the mechanism is as proposed, we would expect that the

change in surface temperature between the true contacts will be a smaller proportion of the overall temperature of the surface at the higher speeds than it is at the intermediate speeds. Thus we would expect that the equilibrium wear per revolution would approach the initial wear for very high speeds, that is, the two curves would converge. Some evidence of this can be seen in Figure 12. The same argument will apply to the lower speeds if we substitute time-wise deformation for overall surface temperature in our argument above.

This may explain why two wear rates were not found by Kerridge. The much smaller diameter cylinder used in his experiments would simulate a much higher speed than those at which we ran insofar as the overall surface temperature and temperature change due to the oxide insulation which we have suggested were concerned. This, and the relative insensitivity to temperature of his tool steel pins could reasonably be expected to make such a transition in wear negligibly small.

Another possible explanation of this increase in wear per revolution was that the oxide was acting as an abrasive. This postulate we discarded on the basis of the behavior of the transferred layer when an inert pin was substituted. Had abrasion been occurring, there would have been loose wear products formed from the pin without first passing through the transferred layer. The rate of replacement of the active material in the transferred layer as shown by the slope of that part of the transfer curve would have had

to be less than the slope during build-up. As can be seen, the rate of replacement was larger, and consequently no direct production of loose wear particles by abrasion was occurring.

In summary, our results substantiate the wear theory as proposed by Kerridge for steel rubbing on steel. The wear process consists of three stages: (i) transfer of metal by a welding mechanism, (ii) the oxidation of the transferred layer and (iii) the subsequent removal of the oxide to form a loose wear product. Two distinct rates of wear are present. Initial wear is solely transfer in building up a layer of transferred metal to the cylinder. The energy potential of this layer is being continuously raised, probably in the form of work-hardening. The critical energy level is characterized by a constant value of load times revolutions, and further energy absorption is accomplished by oxidation. The initiation of oxidation is the cause of an increase in wear rate due to the heat insulation effect of the oxide, which acts to raise the temperature between contacts.

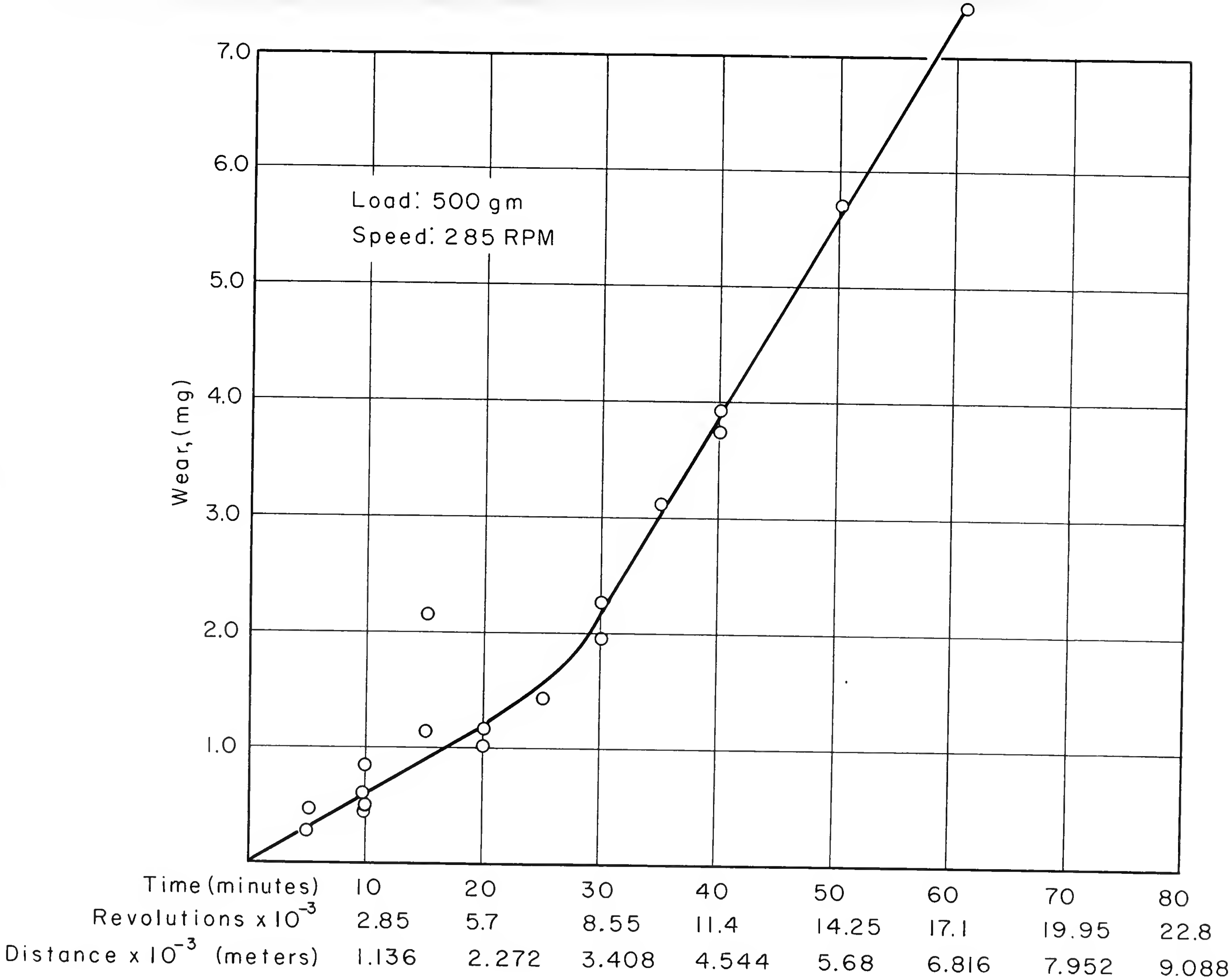


FIG. 1 — WEAR x TIME, REVOLUTION, DISTANCE

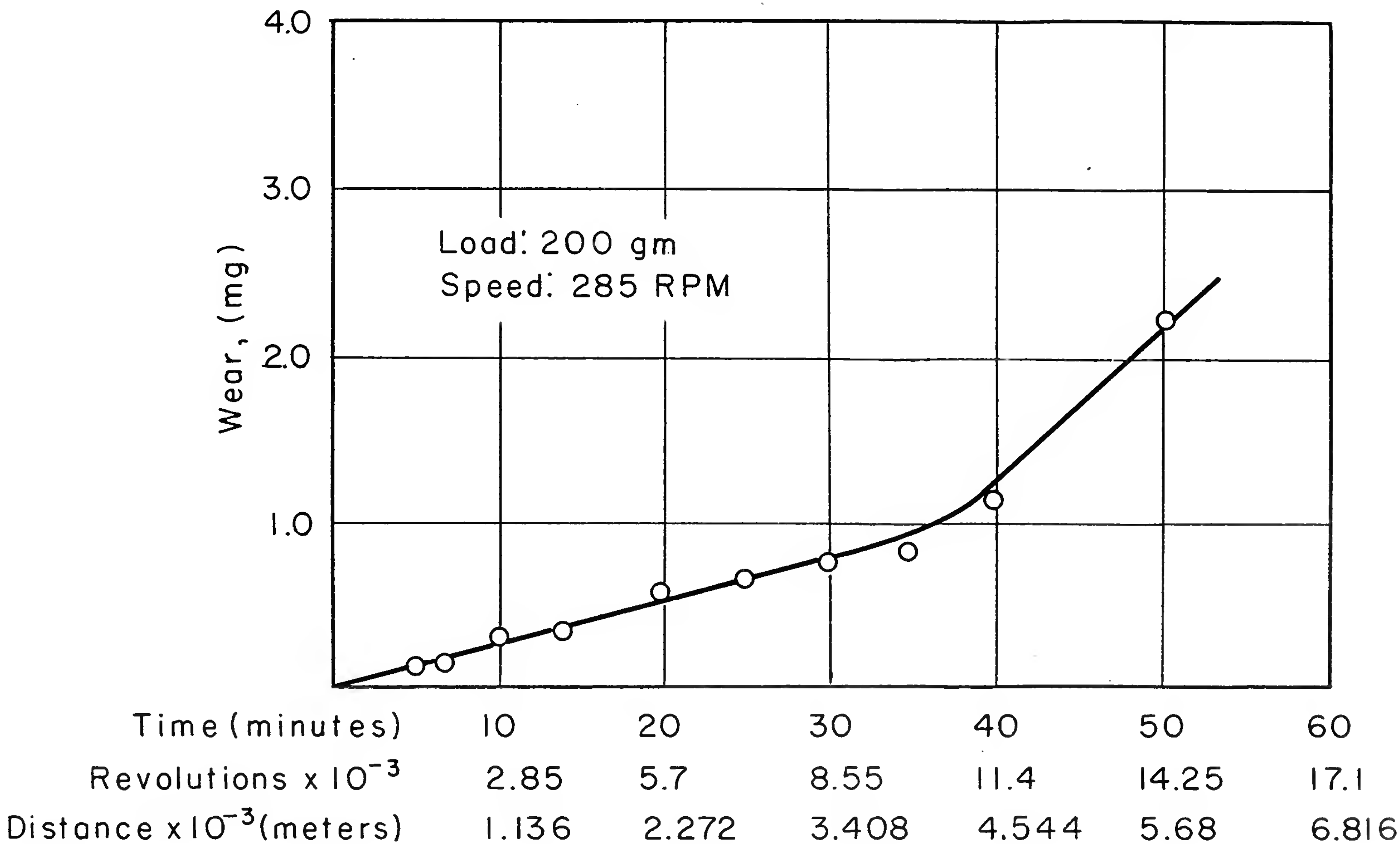


FIG. 2 — WEAR x TIME, REVOLUTION, DISTANCE

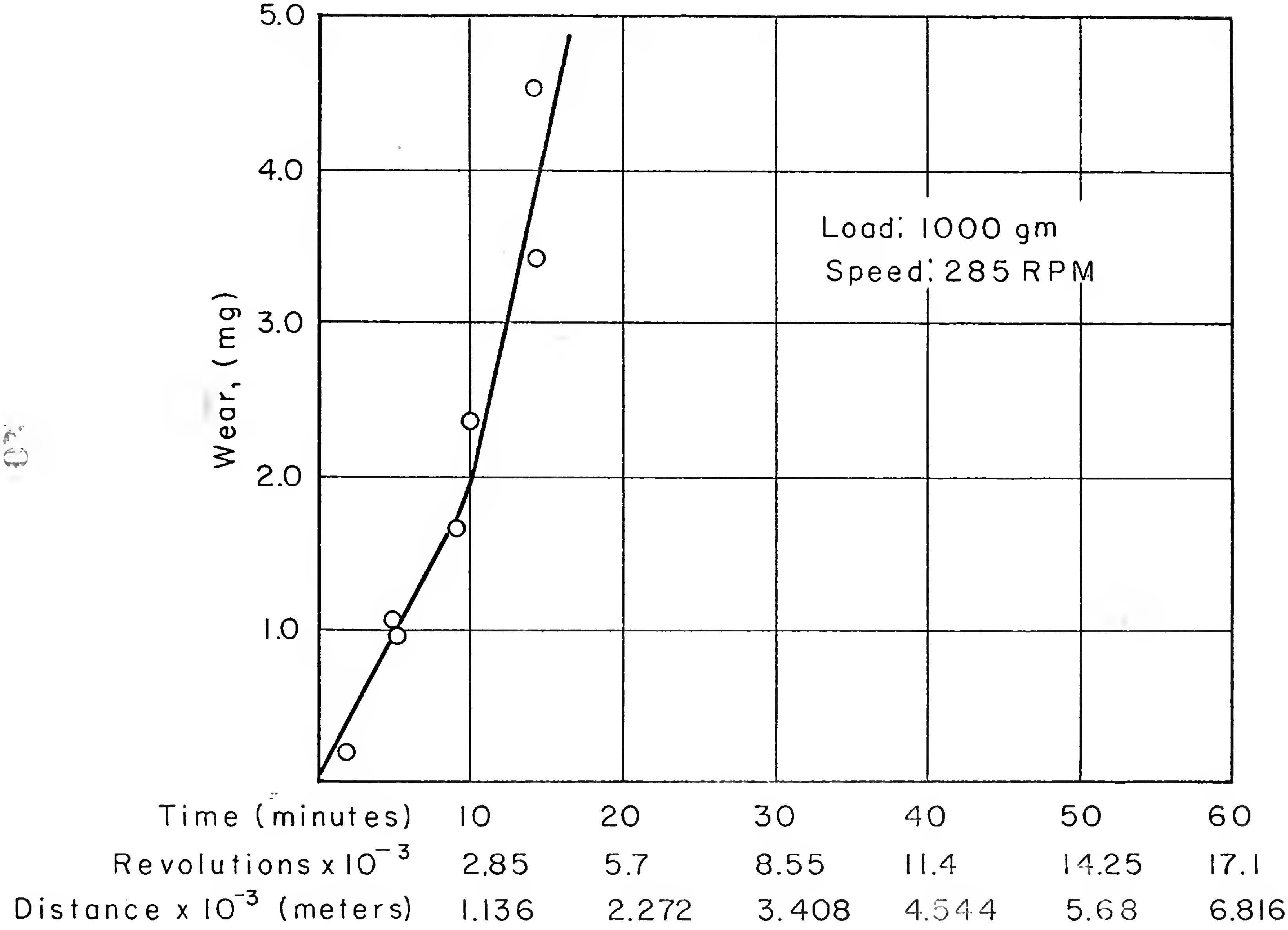


FIG. 3 — WEAR x TIME, REVOLUTION, DISTANCE

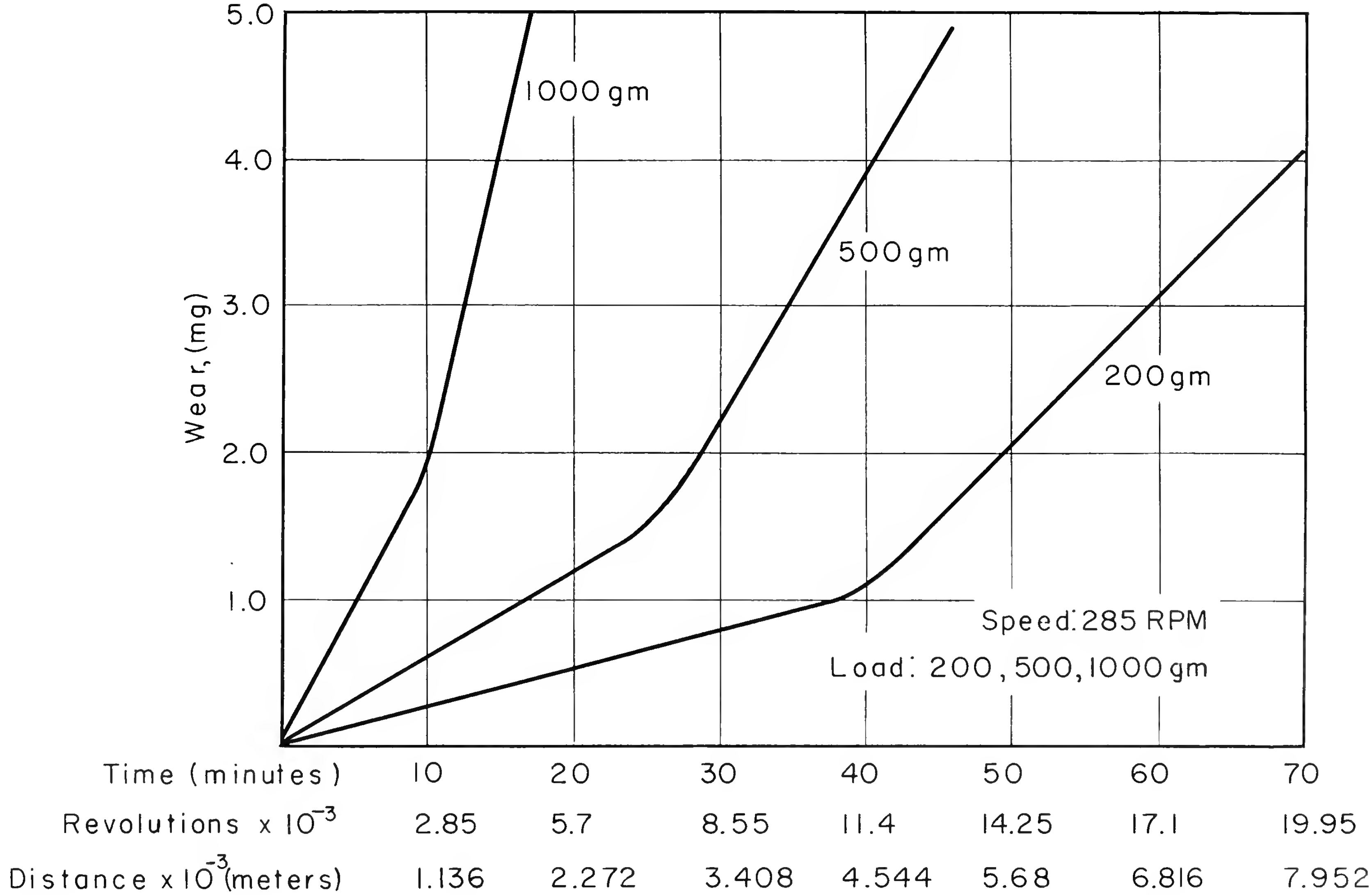


FIG. 4 — COMPARISON OF WEAR

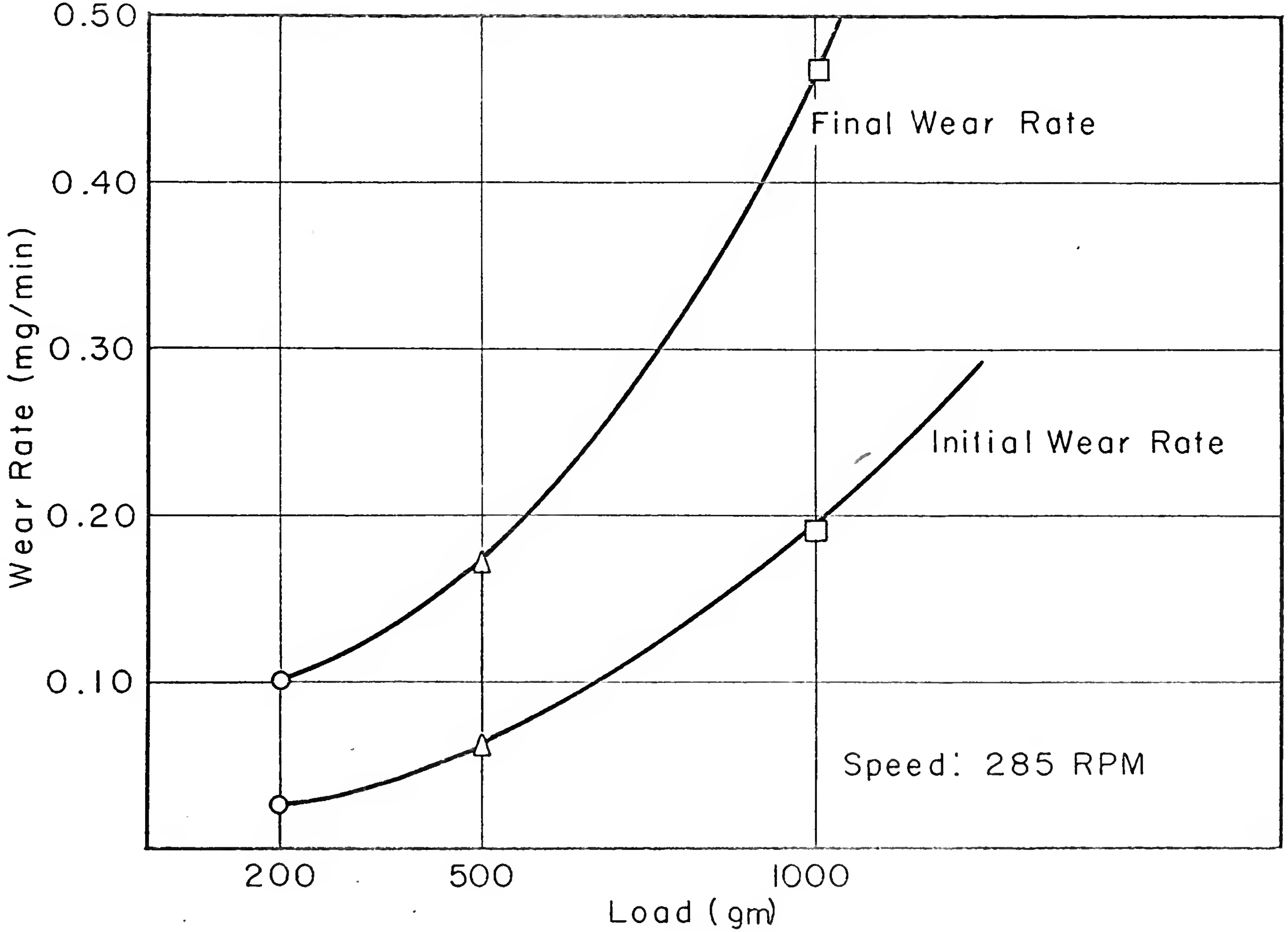


FIG. 5— WEAR RATE x LOAD

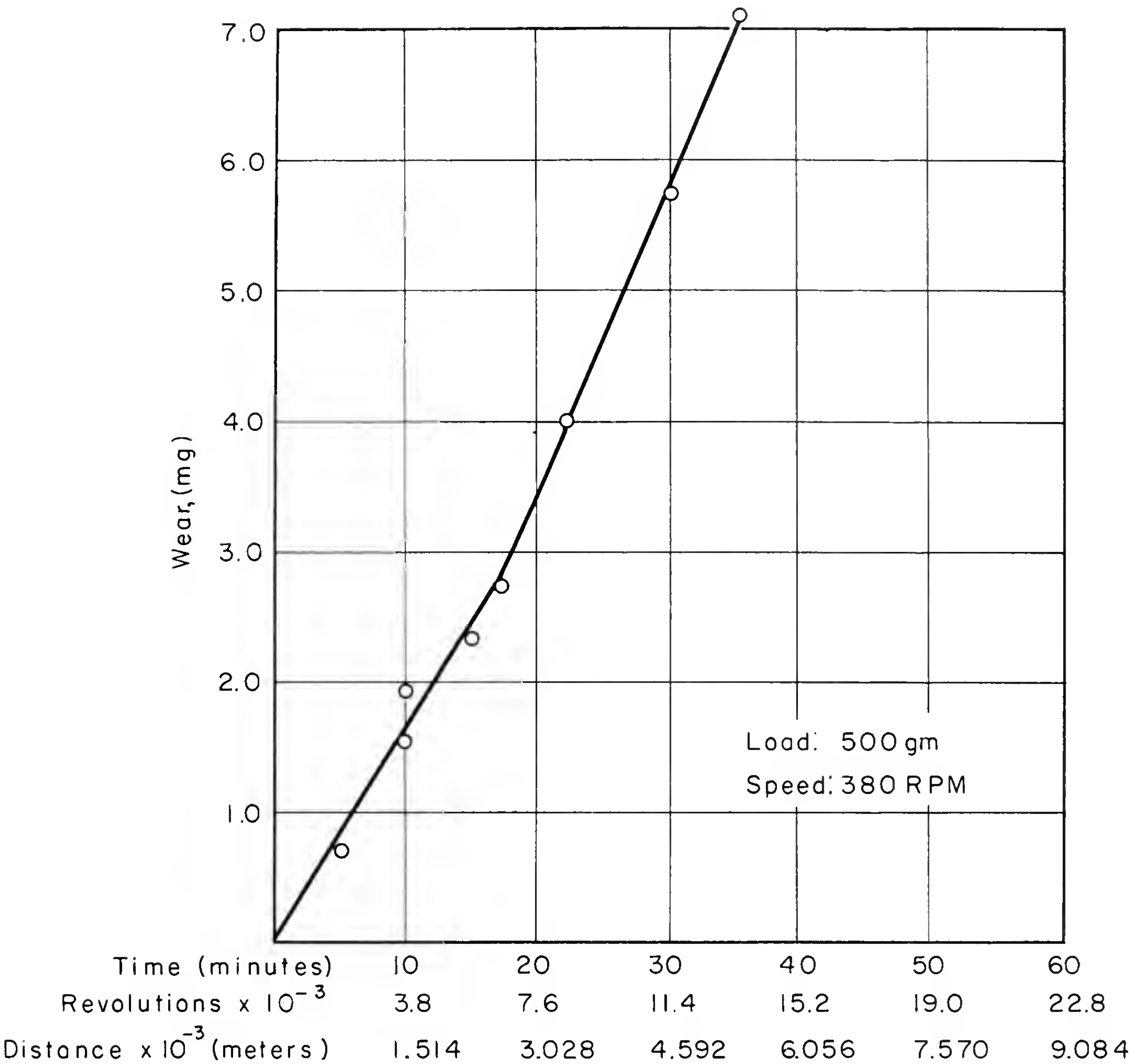


FIG. 6—WEAR x TIME, REVOLUTION, DISTANCE

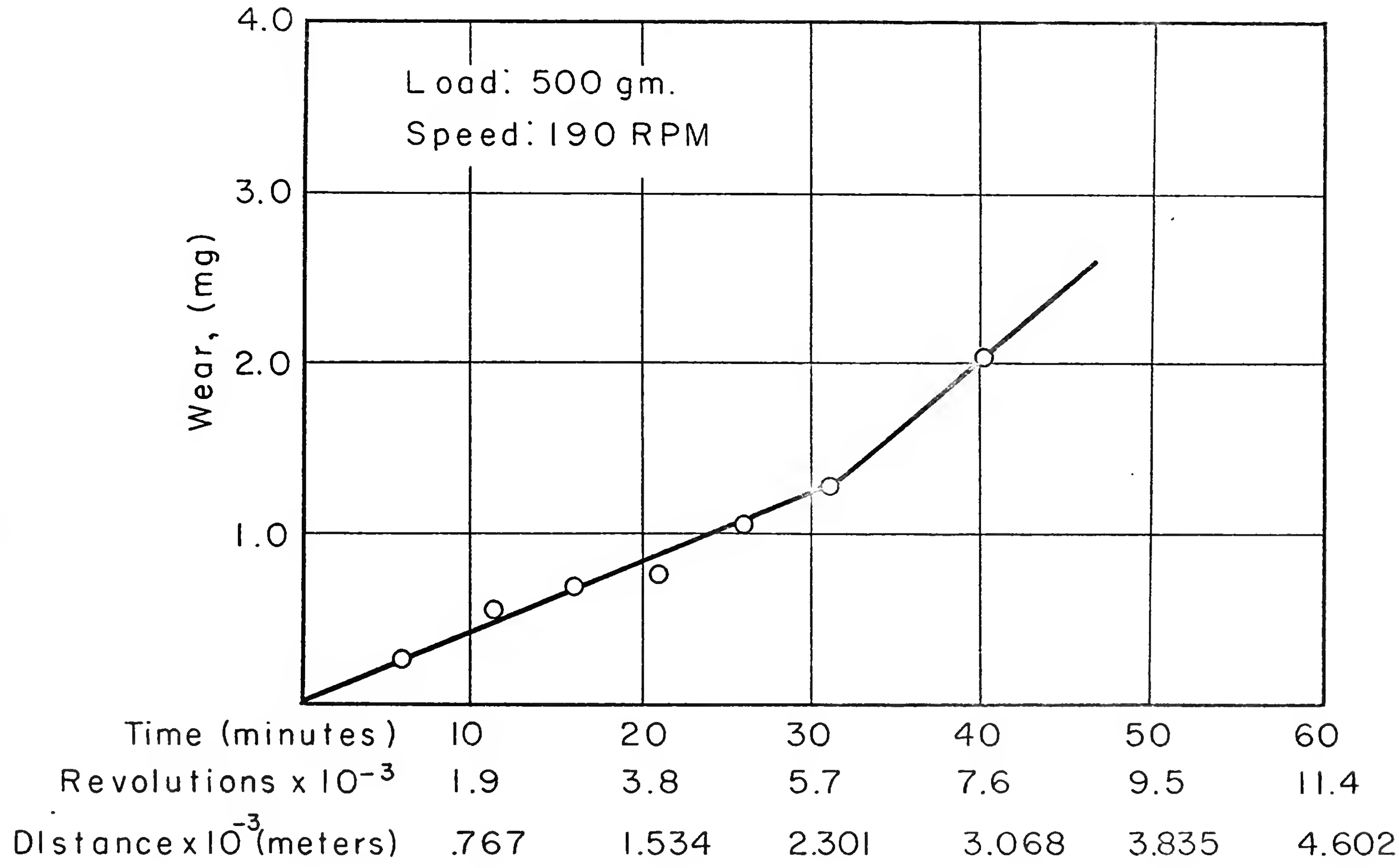


FIG. 7— WEAR x TIME, REVOLUTION, DISTANCE

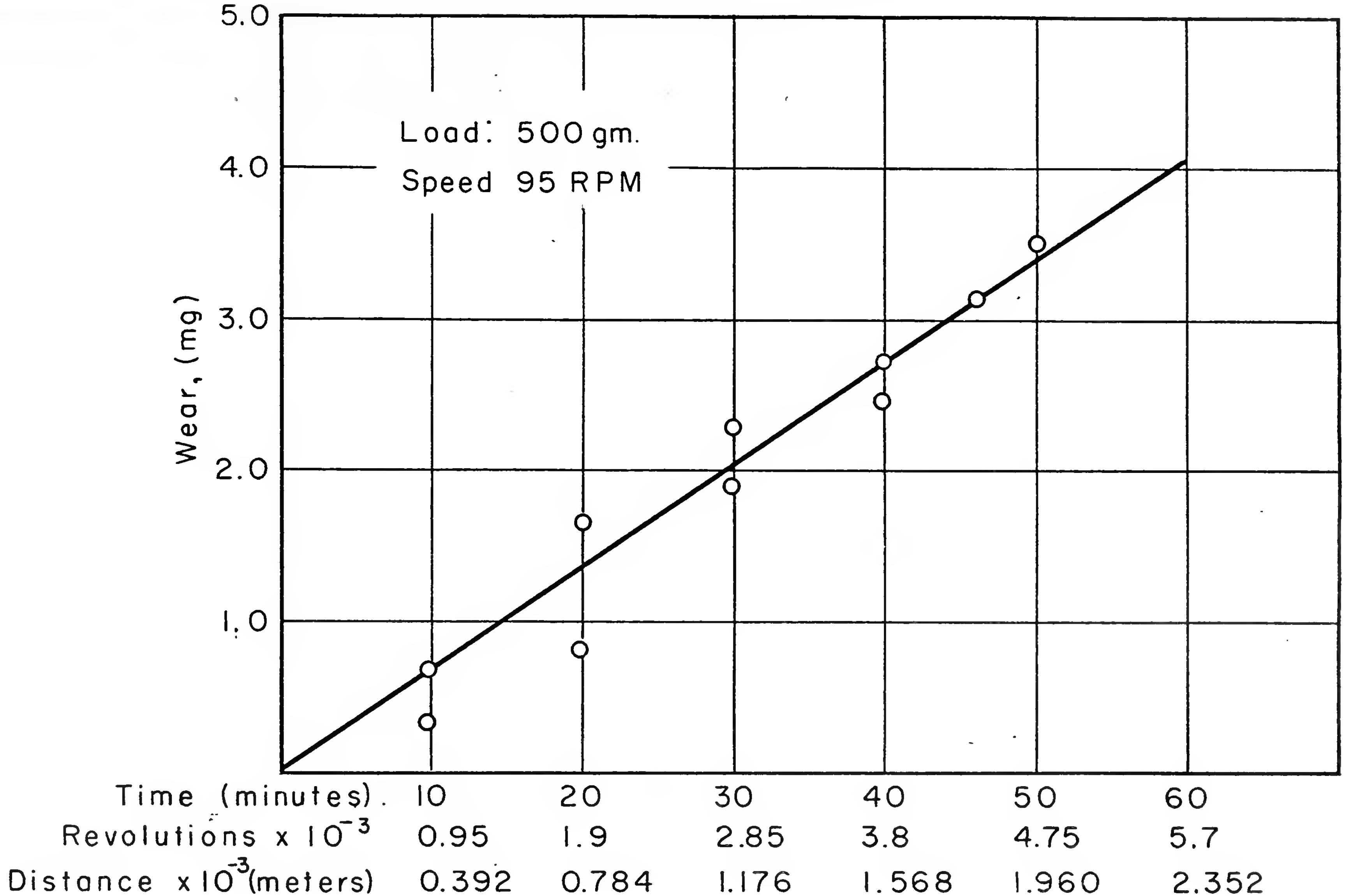


FIG. 8 — WEAR x TIME, REVOLUTION, DISTANCE

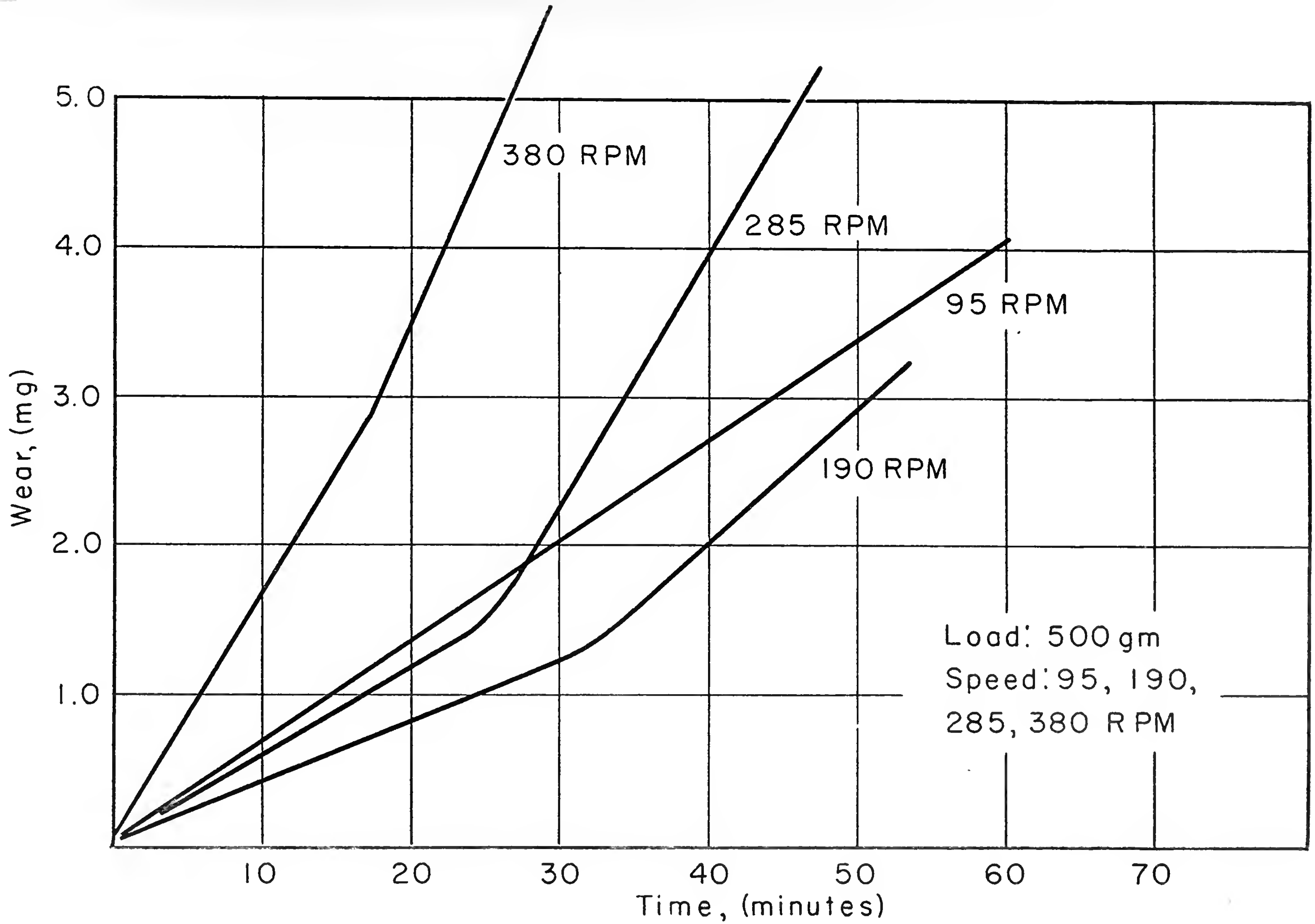


FIG.9—COMPARISON OF WEAR

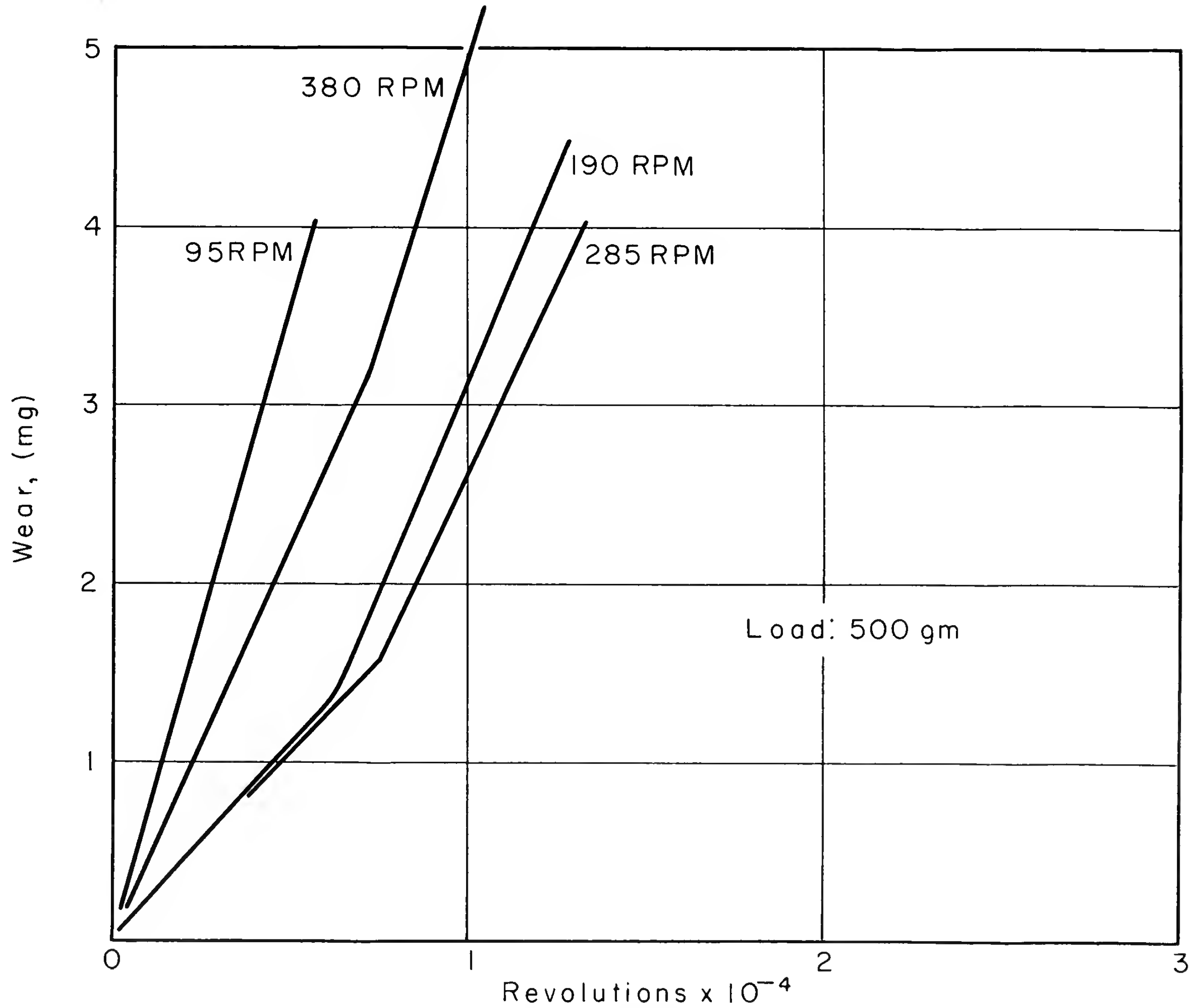


FIG. 10 — COMPARISON OF WEAR AGAINST ROTATION

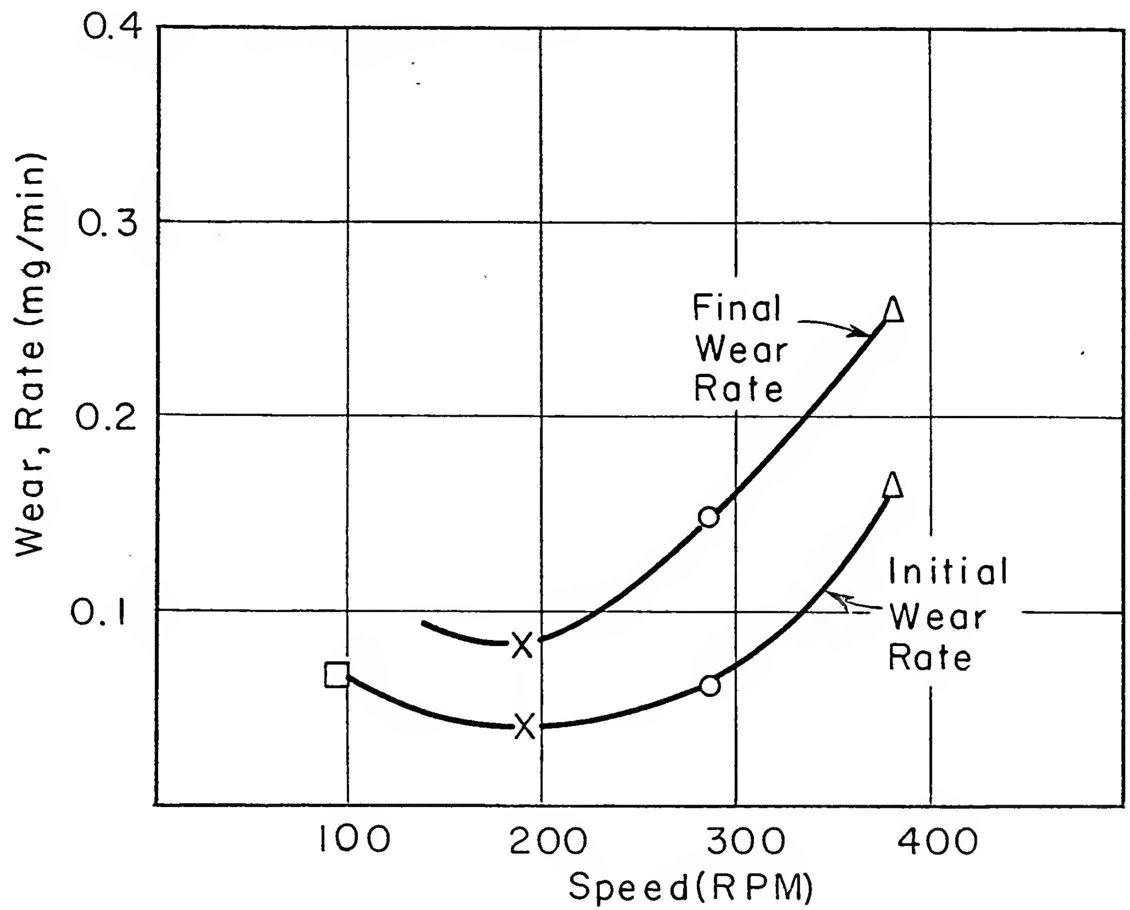


FIG. 11—WEAR RATE x SPEED

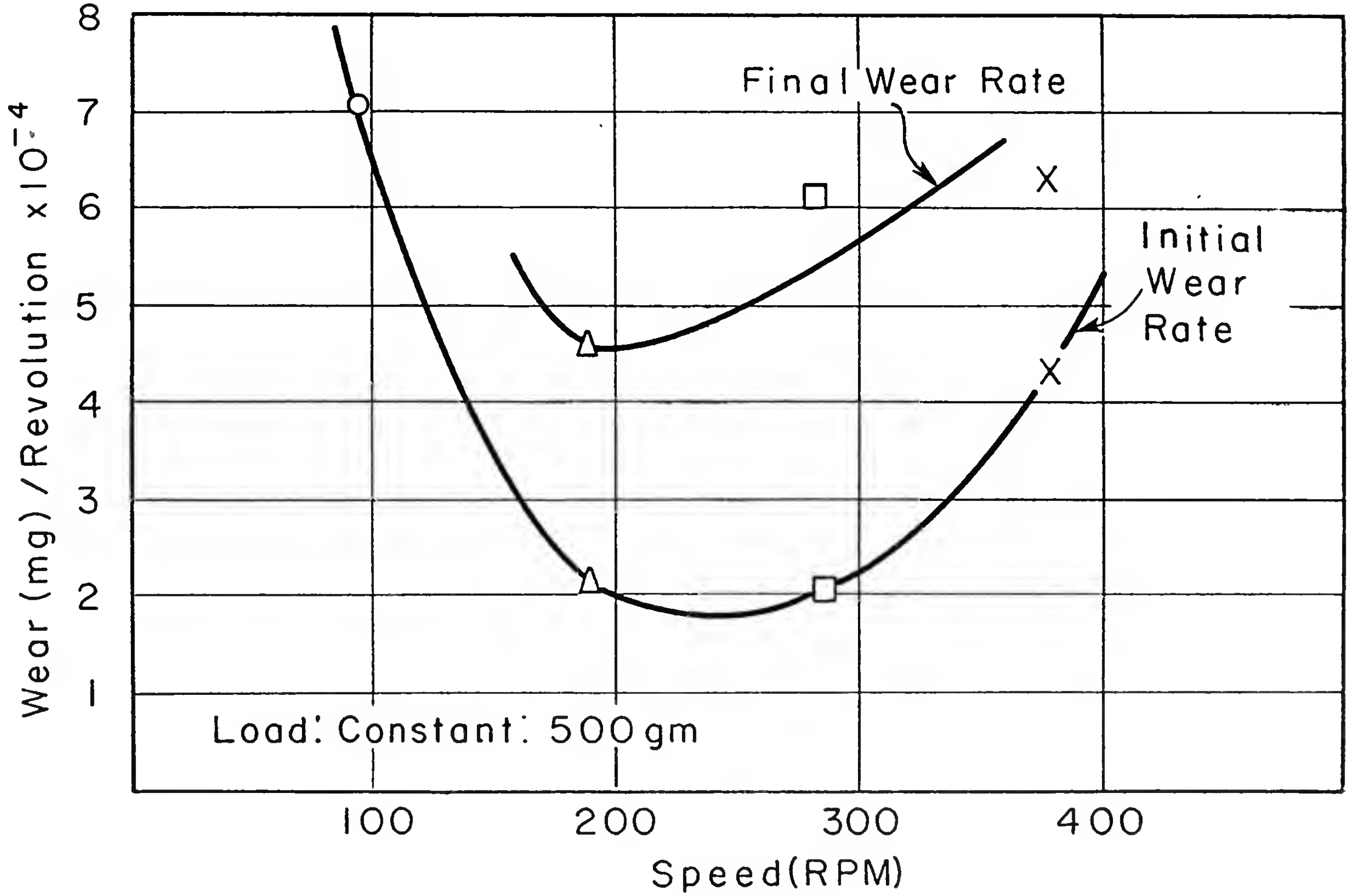


FIG. 12—WEAR PER REVOLUTION x SPEED

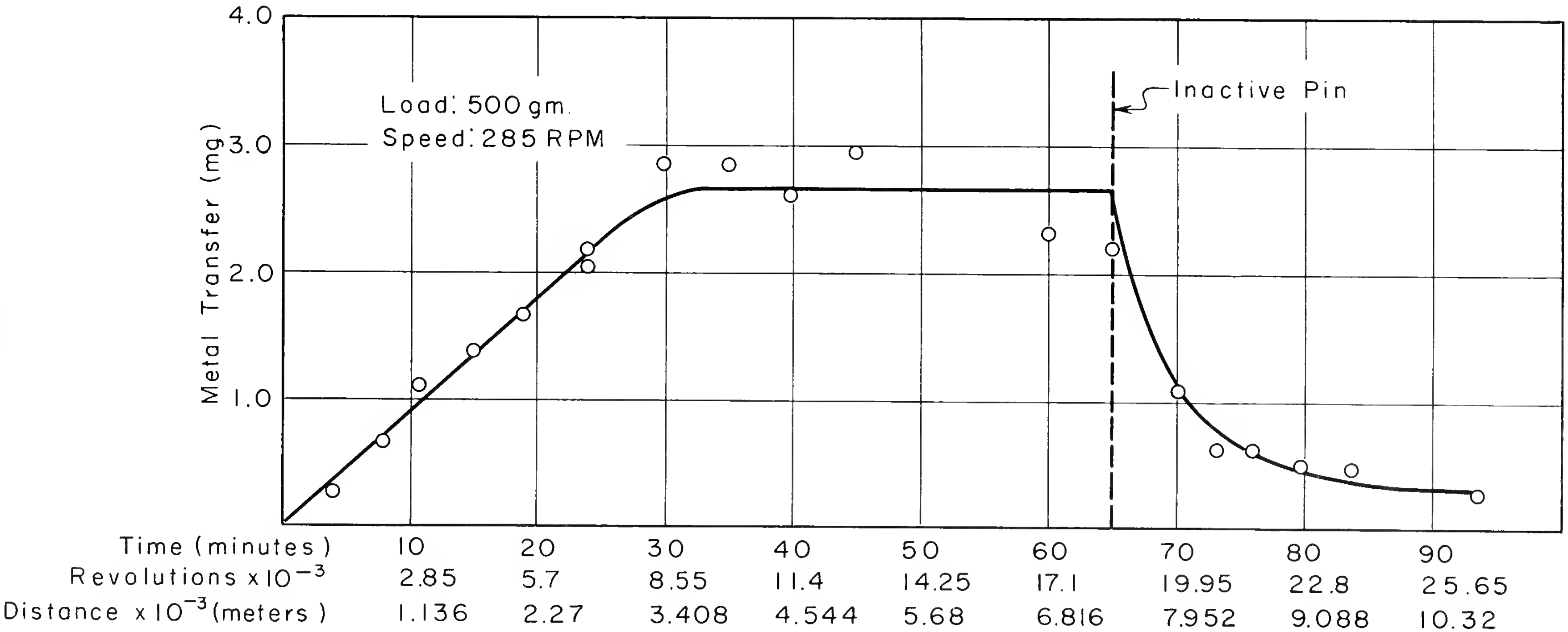


FIG. 13— METAL TRANSFER x TIME, REVOLUTION, DISTANCE

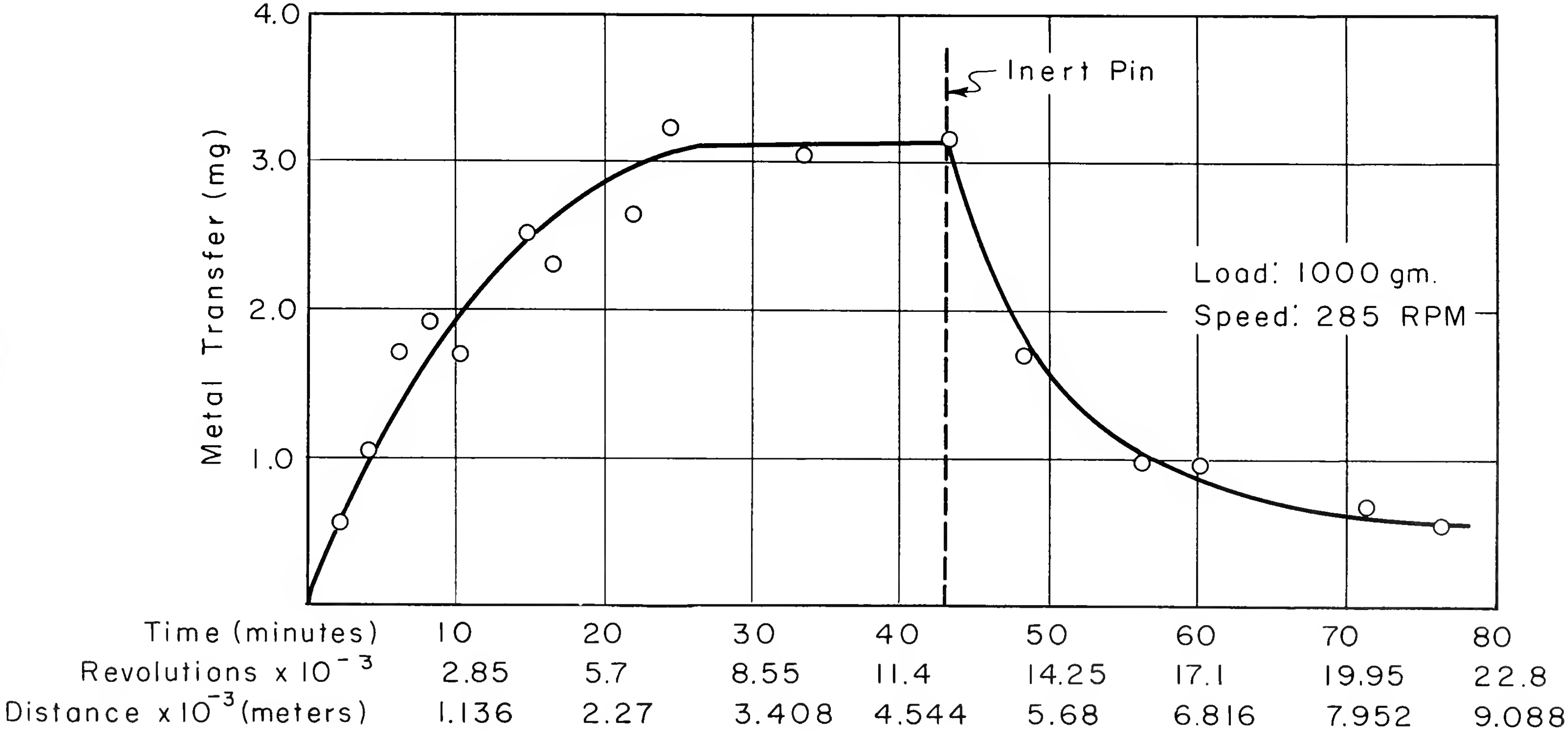


FIG. 14- METAL TRANSFER x TIME, REVOLUTION, DISTANCE

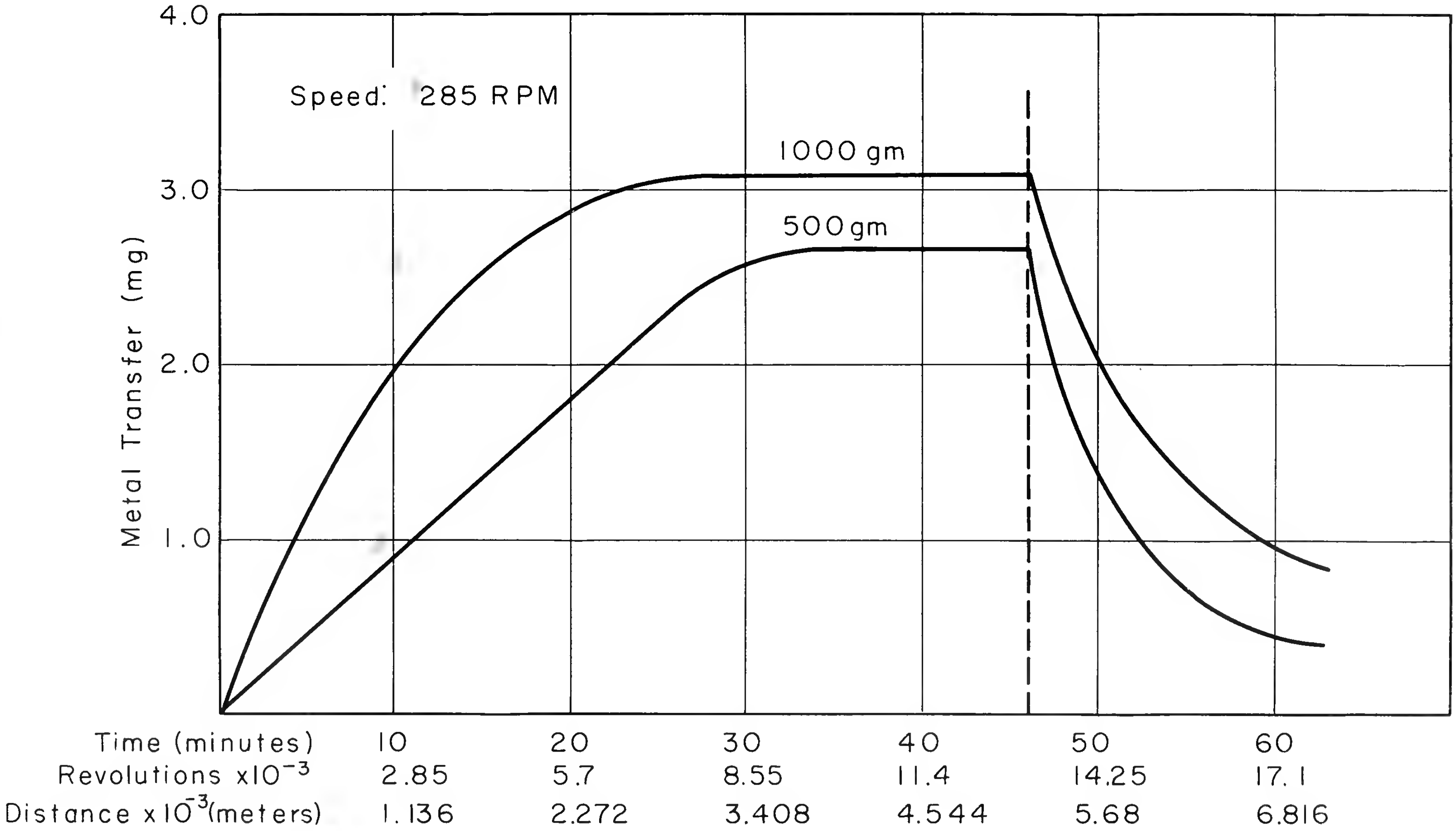


FIG. 15 — METAL TRANSFER COMPARISON

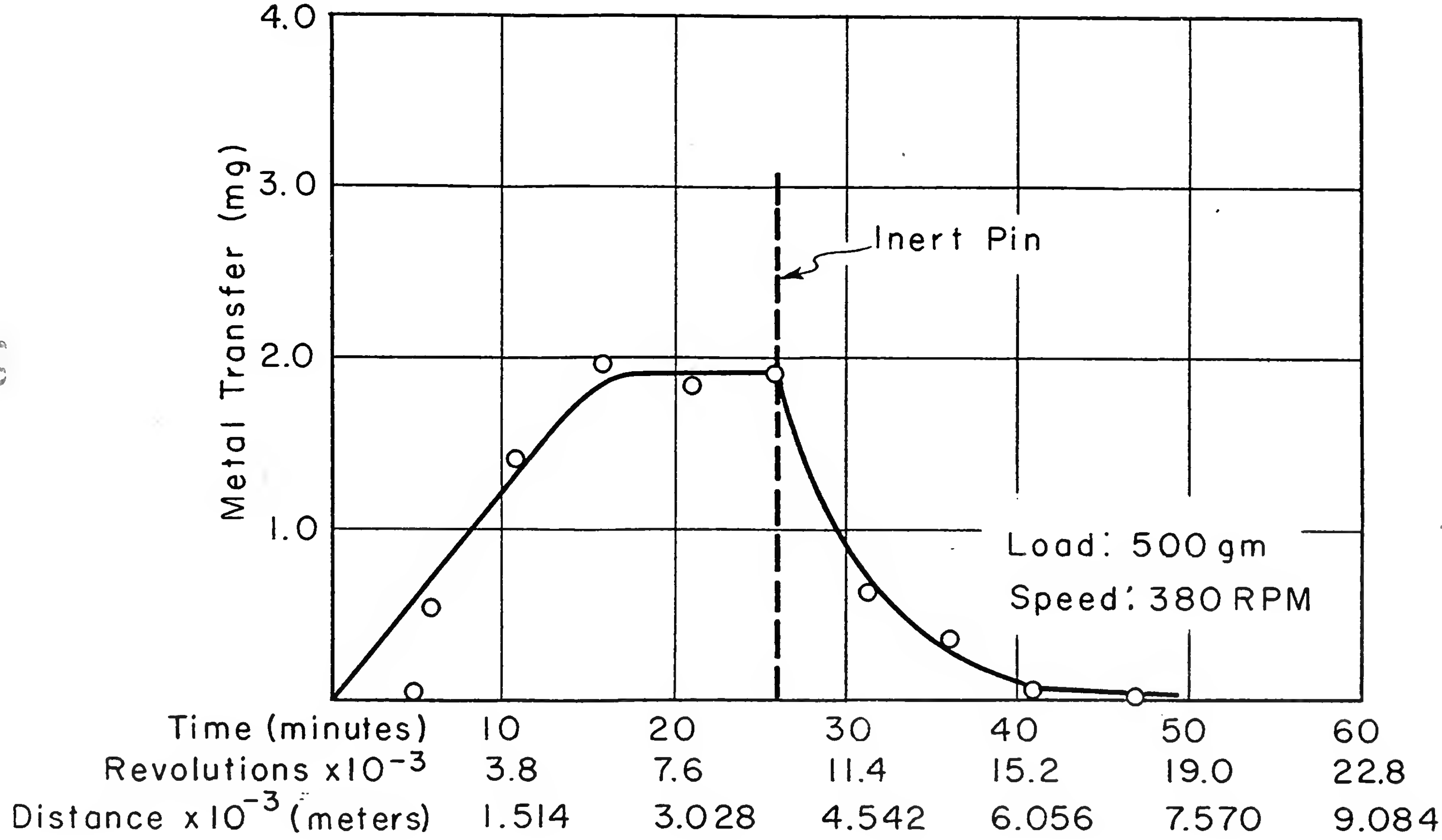


FIG. 16–METAL TRANSFER x TIME, REVOLUTION, DISTANCE

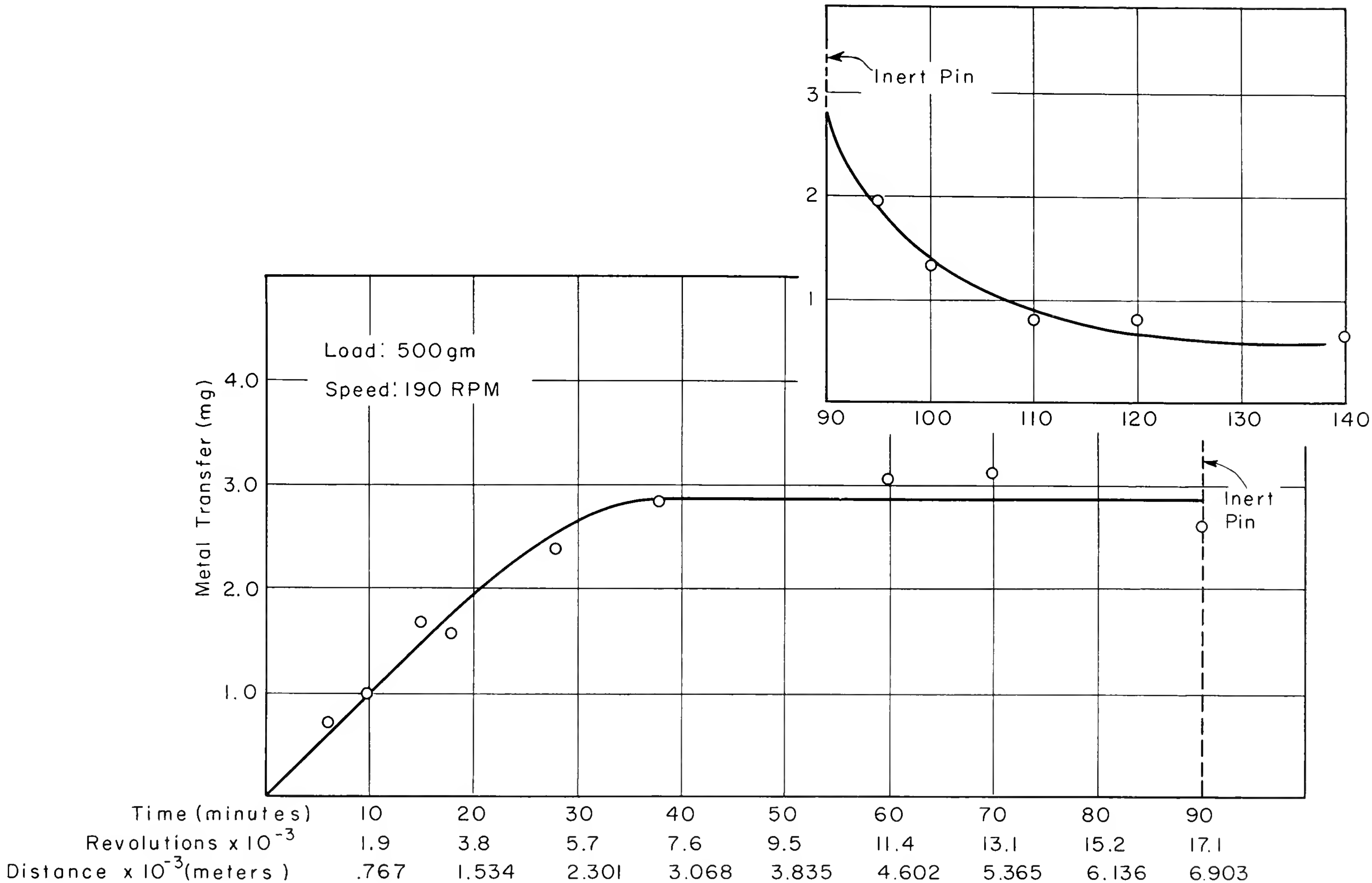


FIG. 17—METAL TRANSFER x TIME, REVOLUTION, DISTANCE

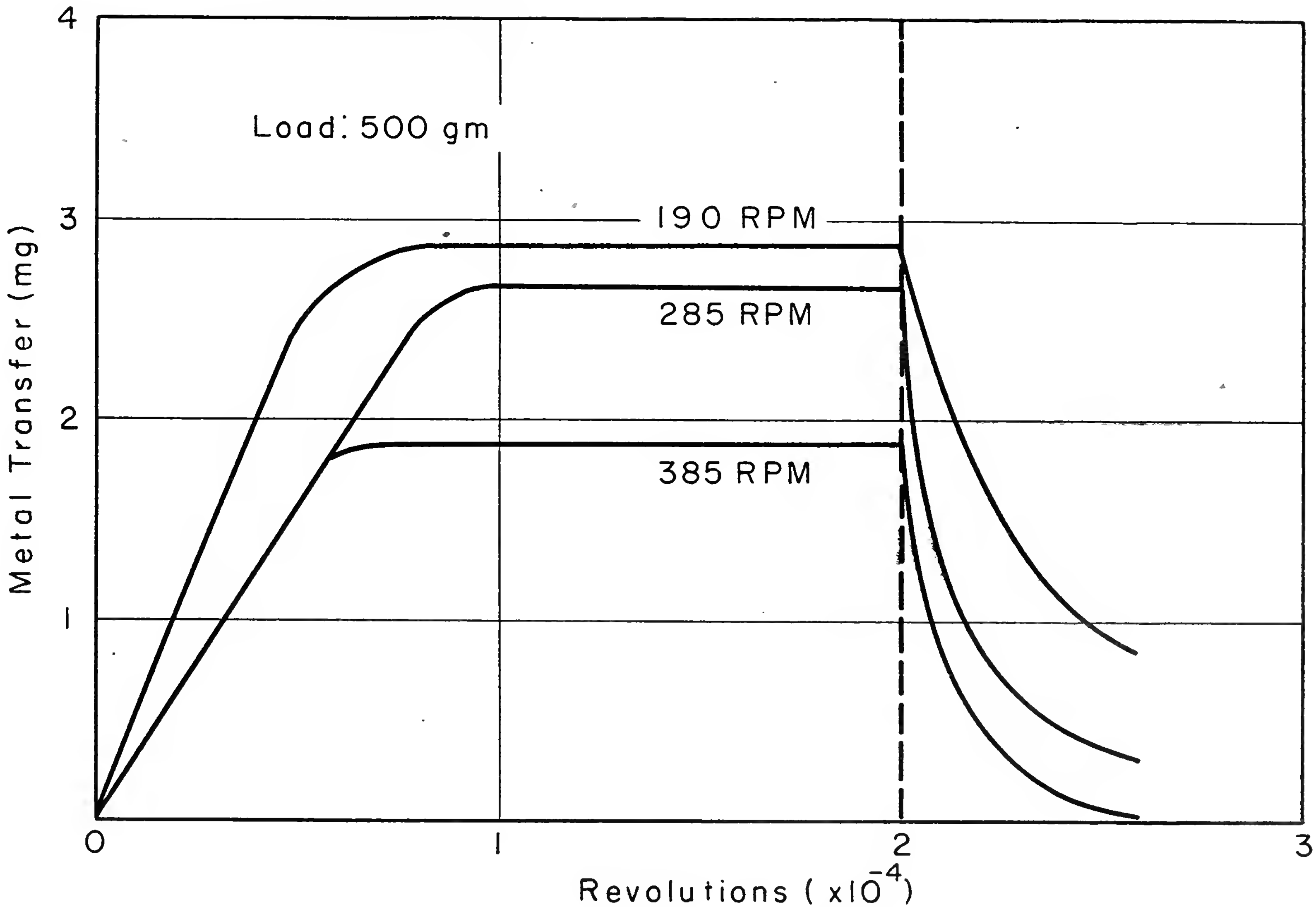


FIG. 18—METAL TRANSFER COMPARISON

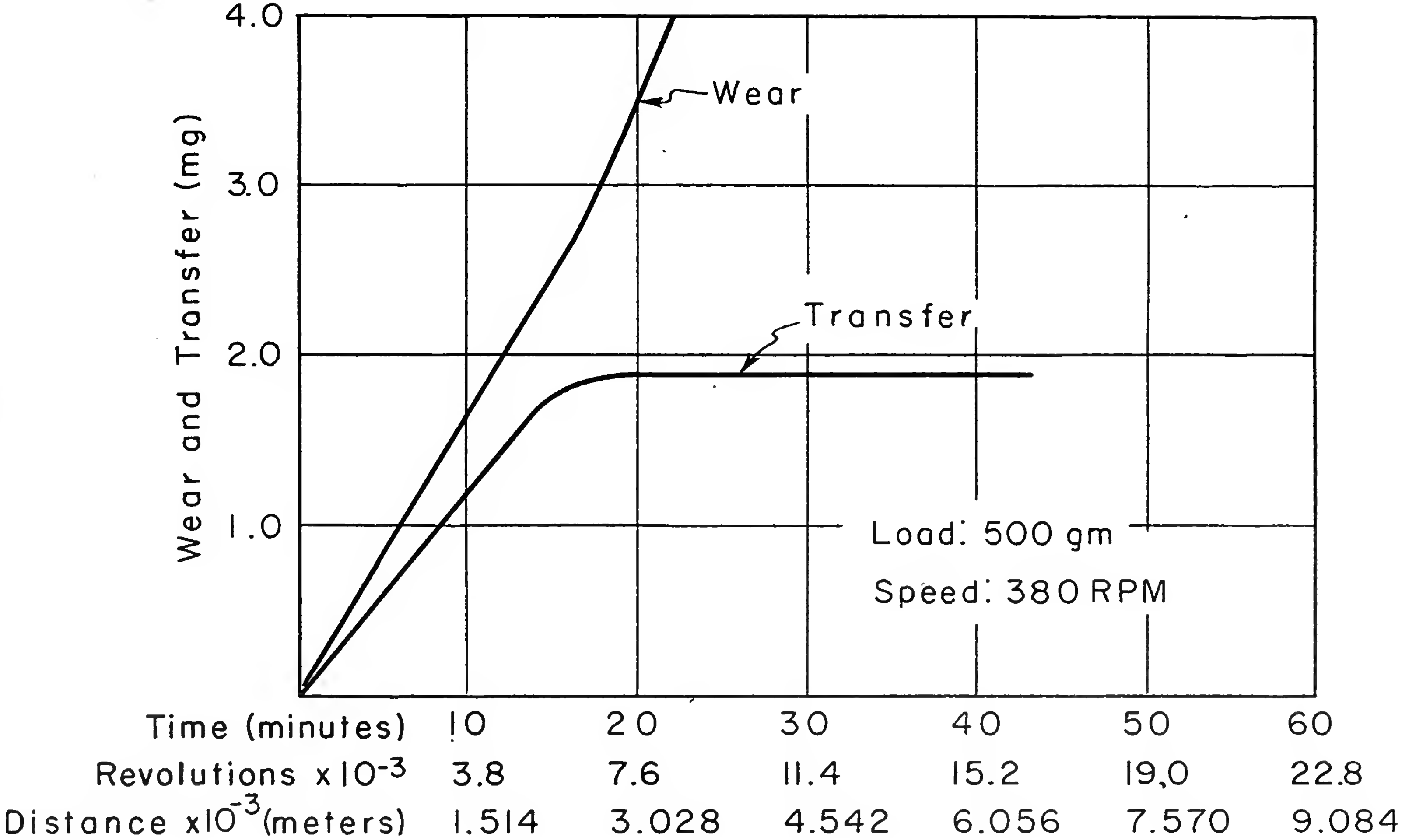


FIG. 19–WEAR AND METAL TRANSFER

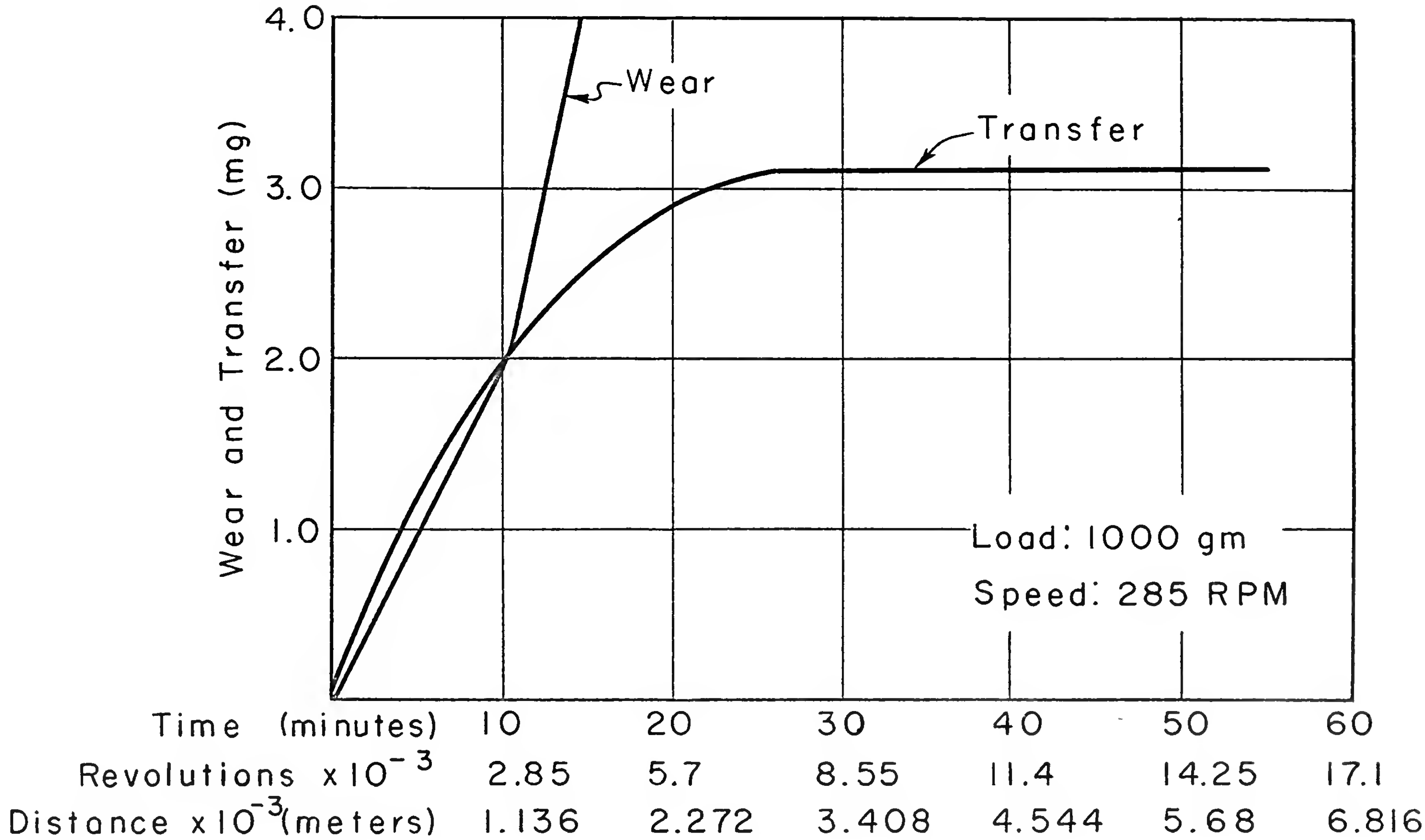


FIG. 20—WEAR AND METAL TRANSFER

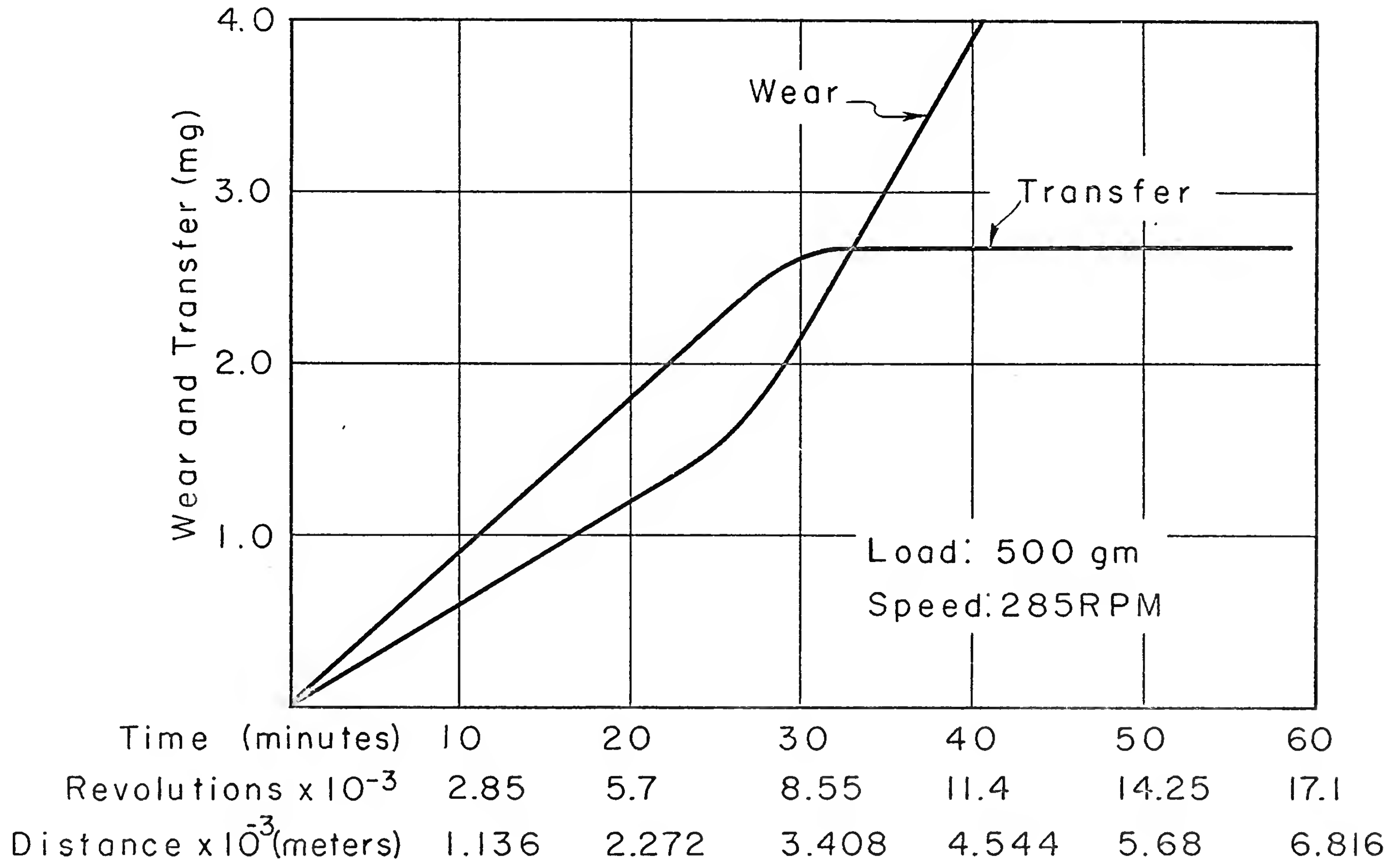


FIG. 21-WEAR AND METAL TRANSFER

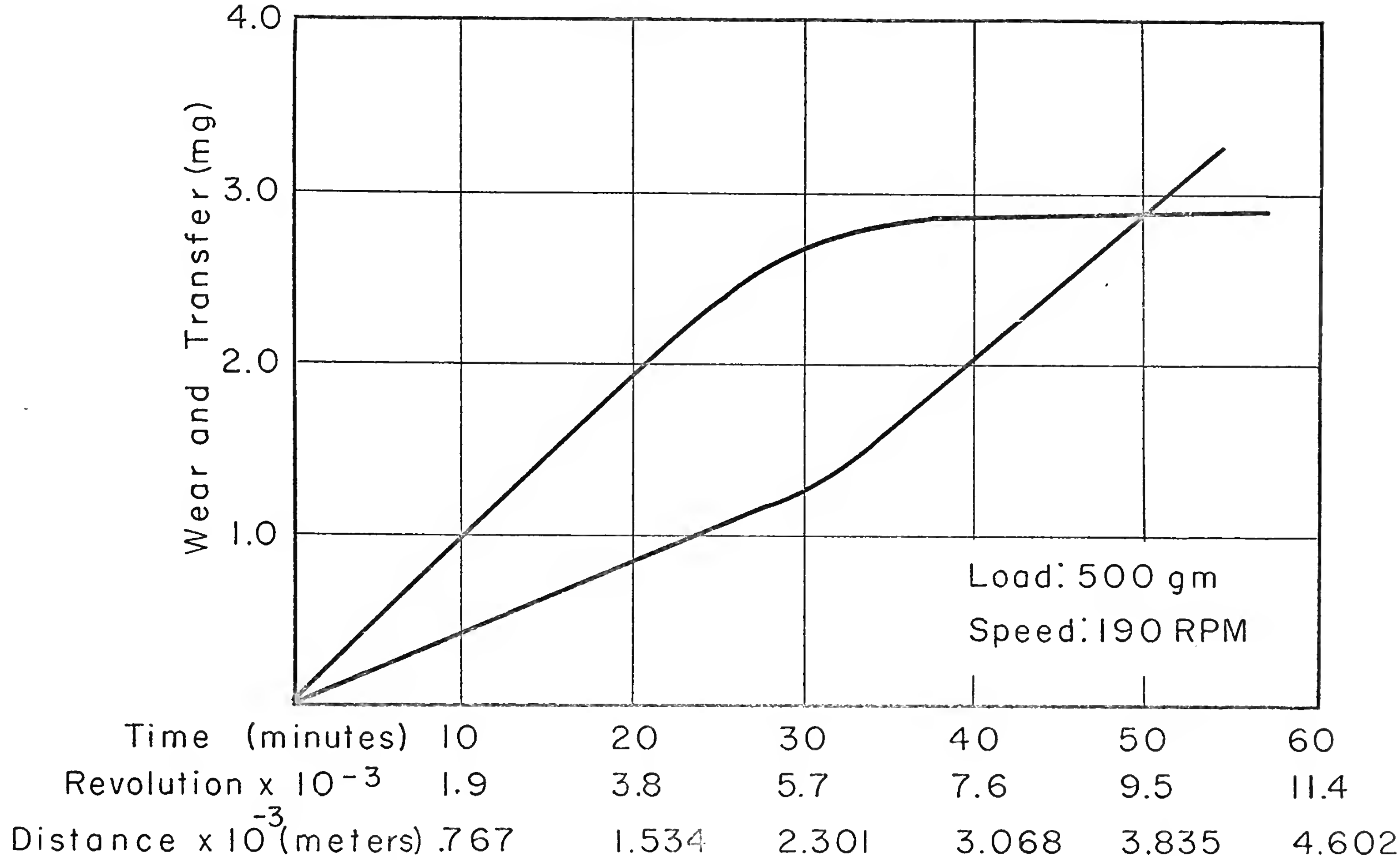


FIG. 22- WEAR AND METAL TRANSFER

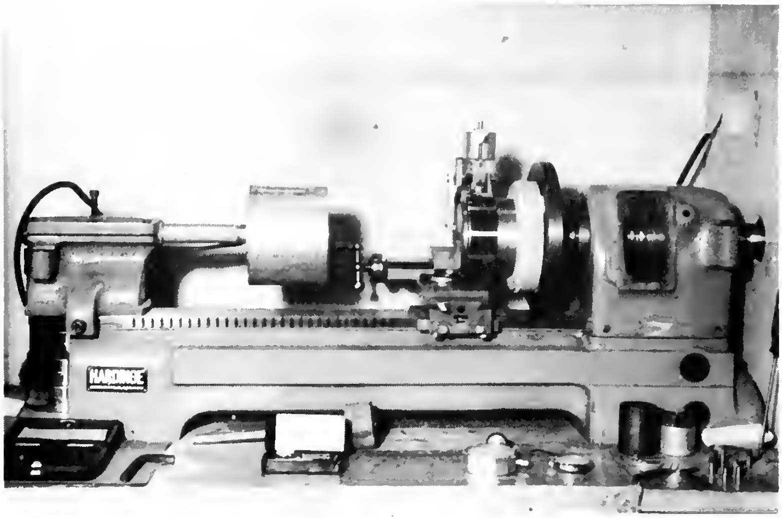


Fig. 23 Lathe with the cylinder and the pin; at left is the atmospheric shield that encloses the cylinder when running the experiments.

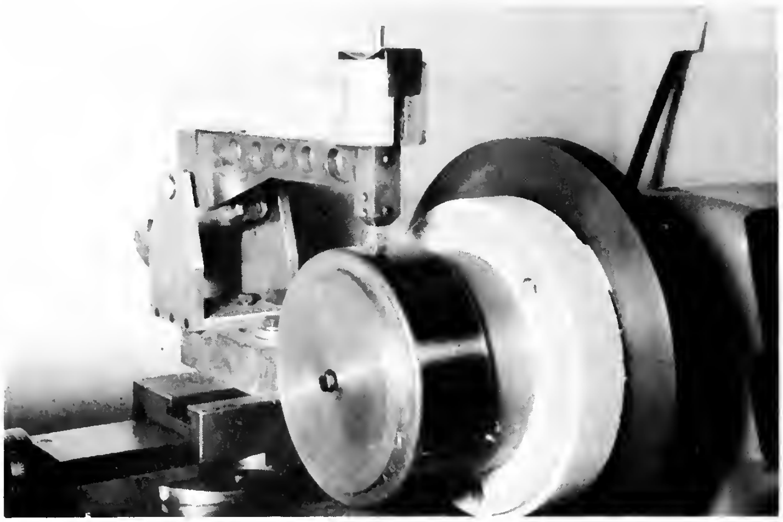


Fig. 24 Detail of the cylinder and pin loading device.

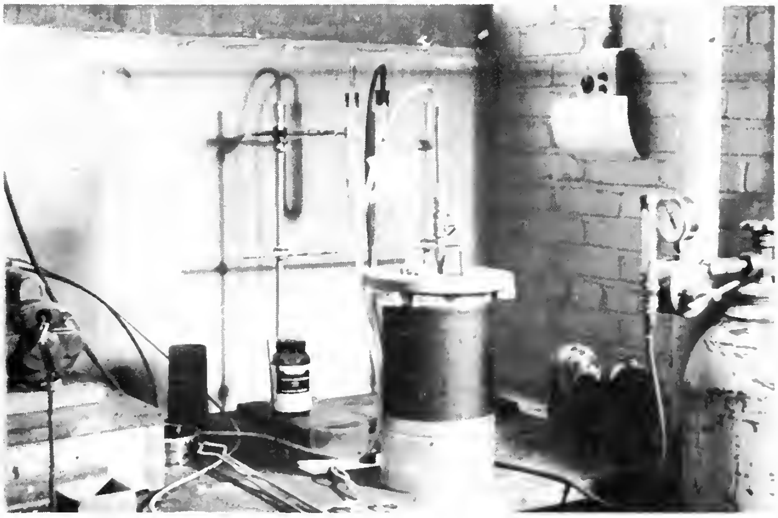


Fig. 25 Atmospheric Supply.

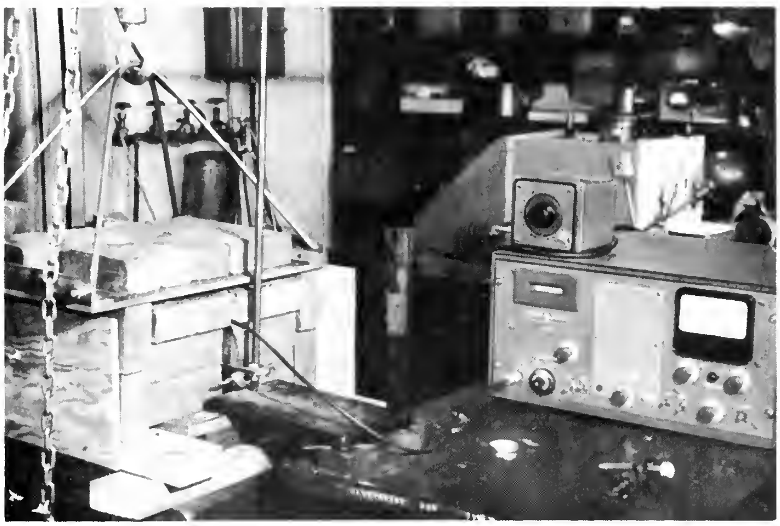


Fig. 26 Lead castle; at left enclosure of lead block over lathe inside of which is the cylinder and Geiger tube; at right the scaler.

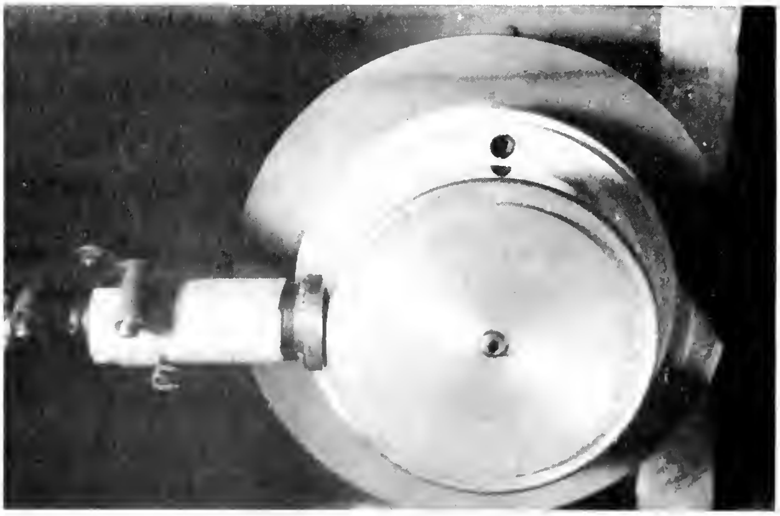


Fig. 27 Detail of the cylinder with the radioactive track and the Geiger tube. This view is inside the lead block enclosure. The rotational axis of the cylinder is vertical.

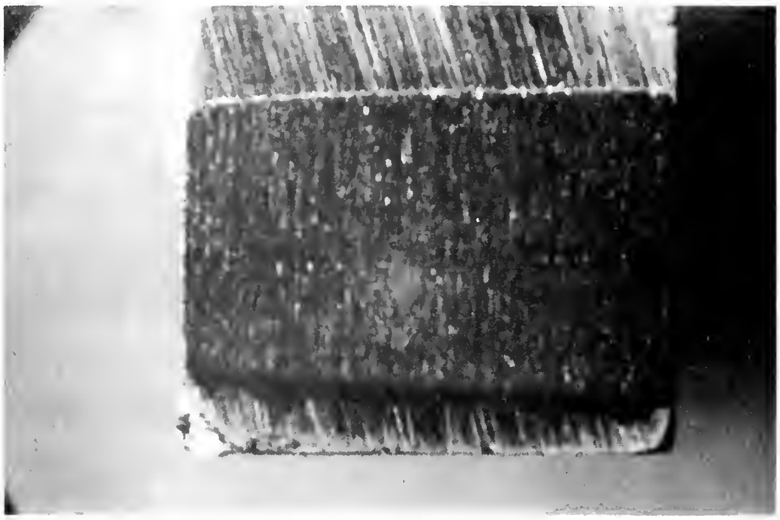


Fig. 28 Wear scar after 40 minutes run. 500 gm load at 285 R. P. M. (pin 1/4 inch square) Leading edge at bottom.

Fig. 29 Leading edge of scar (magnification 35x). 40 minutes run with 500 gm at 285 R. P. M.

Fig. 30 Same as above but with 95x magnification.

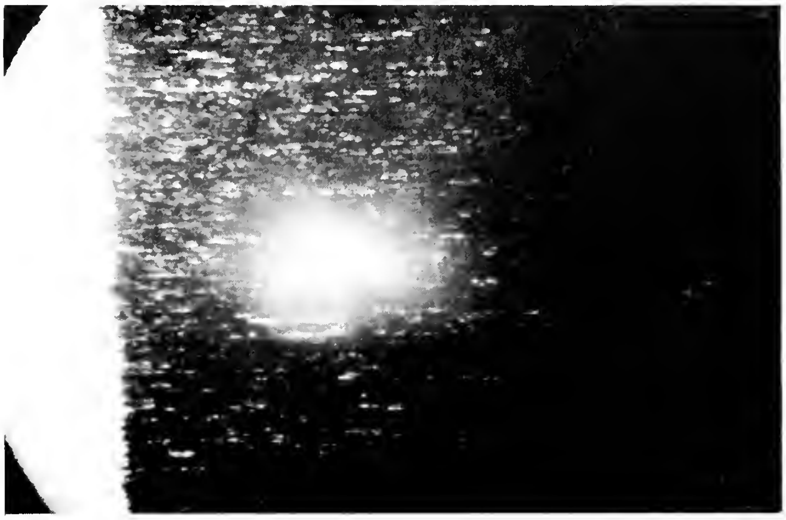


Fig. 31 Trailing edge, magnification 35x, 40 minutes run with 500 gm load at 285 R. P. M.

Fig. 32 Same as above but with 95x magnification.

Fig. 33 Leading edge, magnification 35x, load 200 gm at 285 R. P. M.

Fig. 34 Same as above, trailing edge.

Fig. 35 Leading edge, magnification 35x, load 1000 gm at 380 R. P. M.

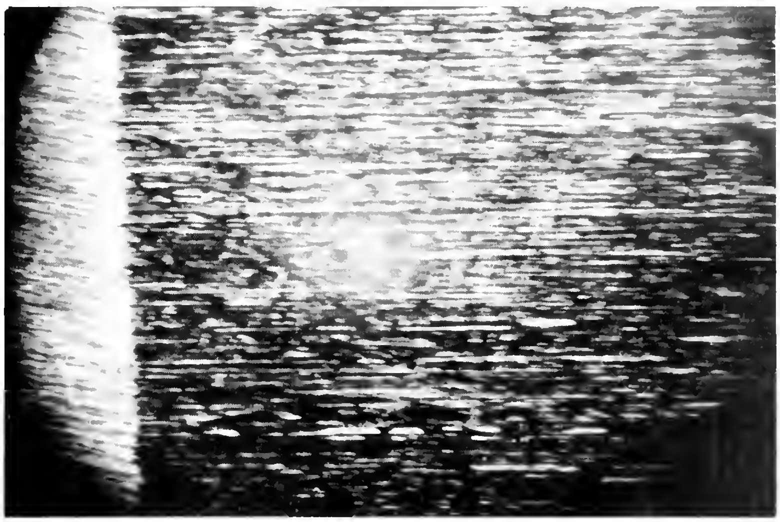


Fig. 36 Same as above, trailing edge.

IV. CONCLUSIONS

1. The wear mechanism, under our particular conditions, is a three stage process as Kerridge proposed, involving transfer of metal by welding to form a built-up layer, its conversion to oxide, and the removal of this oxide by rubbing to form a loose wear product at the same rate that new material is transferred into the built-up layer.
2. The layer of transferred material in the final, or equilibrium, phase is continuously being replaced by new material.
3. Two distinct rates of wear, initial and equilibrium, were observed, with a transition phase between the two corresponding to the beginning of oxide formation. The final wear rate was higher than the initial wear rate.
4. The initial wear consists of metal transfer by welding to the cylinder. This continues until the energy state of the built-up layer reaches a critical level of load x revolutions, this product being roughly constant over a wide range of loads and speeds.
5. The transition in wear and metal transfer coincided. The beginning of oxide formation at this point is believed to be a means by which the energy input to the transferred layer is absorbed, its work-hardening capacity having been reached.
6. The final or equilibrium wear rate is higher than the initial rate probably due to an increase in the surface

temperature between contacts caused by the heat insulating properties of the oxide present. The magnitude of this effect, and therefore the increase in wear rate between initial and final wear rates, is dependent upon the magnitude of the overall surface temperature and the time increment during which a set of contacts are together.

V. RECOMMENDATIONS

The primary difficulty in the work we have done was the low activity level of our radioactive pins. Stronger pins should be processed, and a more precise determination made of the replacement of active material in the transferred layer in the equilibrium phase. This rate of replacement should be the same as the final wear rate if no direct production of loose wear particles is in fact true.

Unfortunately we were unable to reach that part of our work where we proposed to vary the diameter of our cylinders. This parameter should serve as an excellent check on our conclusions as to the factor of load x revolutions being critical in initiating oxide formation. Therefore, we recommend that the next parameter to be investigated be a series of diameters.

The upper and lower ranges of speed should be investigated. This work can be expected to verify the convergence of the curves of initial and final wear per revolution.

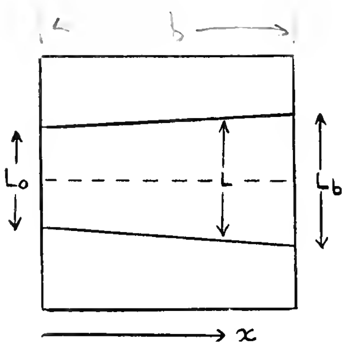
It is recommended that the effect of an inert atmosphere be investigated. The absence of oxygen should greatly affect the oxide formation and a different mechanism must be expected at the critical energy level of the transferred layer. The initial wear rate should be unaffected by the absence of oxygen if the proposed mechanism of transfer by welding is the only mechanism of transfer.

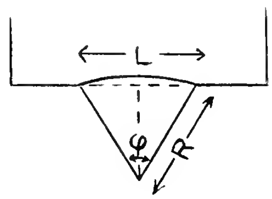
VI. APPENDIX

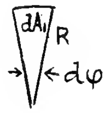
Appendix A

Sample Calculation

For calculating the volume of material worn from the pin it was assumed that the wear scar was a cylindrical section as seen below in the plan and elevation view





From the infinitesimal strip  we have:

$$dA_1 = \frac{R \cdot d\varphi \times R}{2}$$

$$\therefore A_1 = \frac{1}{2} R^2 \int_0^{\varphi} d\varphi = \frac{1}{2} R^2 \cdot \varphi$$

The circle segment's area is:

$$A = A_1 - 2\left(\frac{R \cdot \sin \varphi/2 \times R \cdot \cos \varphi/2}{2} \right)$$

$$A = \frac{1}{2} R^2 \cdot \varphi - R^2 \cdot \sin \varphi/2 \cdot \cos \varphi/2$$, but $\sin\varphi = 2 \cdot \sin \varphi/2 \cdot \cos \varphi/2$

Hence: $$A = \frac{R^2}{2}(\varphi - \sin\varphi)$$

$$\sin\varphi = \varphi - \frac{\varphi^3}{3!} + \frac{\varphi^5}{5!} - \dots$$

so $A \doteqdot \dfrac{R^2 \varphi^3}{2 \times 6}$ but $\varphi = \dfrac{L}{R}$ $\therefore A \doteqdot \dfrac{L^3}{12R}$

$$dV = \frac{L^3}{12R}\,dx$$

Integrating we have: $V = \frac{1}{12R}\int_0^b L^3\,dx = \frac{b}{12R}L_m^3$

where L_m is:

$$L = L_o + (L_b - L_o)\frac{x}{b}$$

$$\int_0^b L^3\,dx = \int_0^b \left[L_o^3 + 3L_o^2(L_b - L_o)\frac{x}{b} + 3L_o(L_o - L_b)^2\frac{x^2}{b^2} + (L_b - L_o)^3\frac{x^3}{b^3} \right] dx =$$

$$= L_o^3 . b + 3L_o^2 . (L_b - L_o)\frac{b}{2} + 3L_o . (L_b - L_o)\frac{b}{3} + (L_b - L_o)^3\frac{b}{4}$$

so: $L_m^3 = L_o^3 + \frac{3}{2}L_o^2 . (L_b - L_o) + L_o(L_b - L_o)^2 + \frac{1}{4}(L_b - L_o)^3$

A travelling microscope was used to measure L_b, L_o and b.

APPENDIX B

Bibliography

1. Bowden, F. P. and Tabor, D., "The Friction and Lubrication of Solids" Oxford University Press, 1953.

2. Burwell, J. T., "Survey of Wear Mechanism" American Society of Lubrication Engineers, April 1955.

3. I-Ming Feng, "Metal Transfer and Wear" Journal of Applied Physics, Volume 23, Number 9, 1952.

4. I-Ming Feng, "Analysis of the Effect of Various Factors on Metal Transfer and Wear Between Specimen Pairs of Same Metal and Same Shape" Journal of Applied Physics, January 1955.

5. Archard, J. F. and Hirst, W., "The Wear of Metals Under Unlubricated Conditions" Proceedings of the Royal Society, A, Volume 236, 1956.

6. Kerridge, M., "Metal Transfer and the Wear Process" Proceedings of the Physical Society, Section B, Volume 68, 1955.

7. Rabinowicz, E., "Quantitative Study of the Wear Process" Proceedings of the Physical Society, Volume 66, 1953.

8. Kerridge, M. and Lancaster, J. K., "The Stages in a Process of Severe Metallic Wear" Proceedings of the Royal Society, A, Volume 236, 1956.

9. Rightmire, B. G., "Statistical Analysis of a Wear Process, 1957.

10. Hirst, W. and Lancaster, J. K., "Surface Film Formation and Metallic Wear" Journal of Applied Physics, Volume 27, Number 9, 1956.

11. Finnie, I. and Rabinowicz, E., "A Radioactive Study of the Metal Cutting Process" American Society of Lubrication Engineers, 1954.

12. Burwell, J. T. and Strang, C. D., "On the Empirical Law of Adhesive Wear" Journal of Applied Physics, Volume 23, Number 18, 1952.

13. Sakman, B. W., Burwell, J. T. and Irvine, J. W., "Measurements of the Adhesion Component in Friction by Means of Radioactive Indicators" Journal of Applied Physics 15, 1944.

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Metal transfer in the wear process.

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Metal transfer in the wear process.